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(12) **United States Patent**
Suich et al.

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(45) **Date of Patent: Jan. 25, 2022**

(54) **LIGHT-EMITTING DIODES, LIGHT-EMITTING DIODE ARRAYS AND RELATED DEVICES**

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(73) Assignee: **CreeLED, Inc.**, Durham, NC (US)

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(22) Filed: **Aug. 20, 2019**

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(Continued)

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H01L 33/60	(2010.01)
H01L 25/075	(2006.01)
H01L 33/50	(2010.01)

(52) **U.S. Cl.**
CPC ***H01L 33/60*** (2013.01); ***H01L 25/0753*** (2013.01); ***H01L 33/505*** (2013.01); *H01L 2933/0091* (2013.01)

(58) **Field of Classification Search**
CPC H01L 2251/5369; H01L 2251/5271–5275; H01L 2251/5284; H01L 51/5268;
(Continued)

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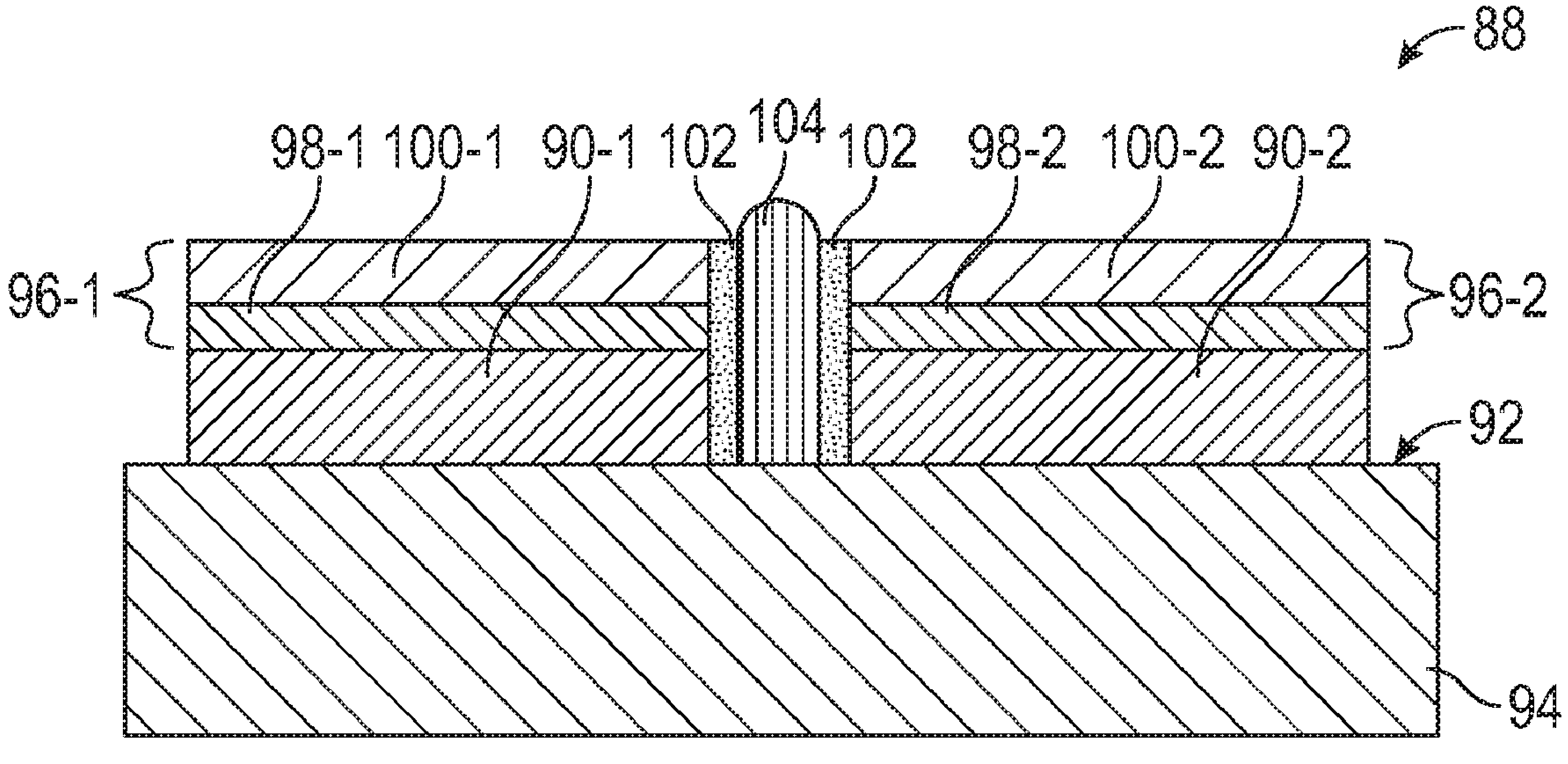
(57) **ABSTRACT**

Light-emitting diodes (LEDs), LED arrays, and related devices are disclosed. An LED device includes a first LED chip and a second LED chip mounted on a submount with a light-altering material in between. The light-altering material may include at least one of a light-reflective material and/or a light-absorbing material. Individual wavelength conversion elements may be arranged on each of the first and second LED chips. The light-altering material may improve the contrast between the first and second LED chips as well as between the individual wavelength conversion elements. The light-altering material may include at least one of nanoparticles, nanowires, mesowires, or combinations thereof. LED devices may include submounts in modular configurations where LED chips may be mounted on adjacent submounts to form an LED array.

39 Claims, 17 Drawing Sheets



Related U.S. Application Data

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(58) **Field of Classification Search**
CPC H01L 51/5275; H01L 33/60; H01L 2933/0091; H01L 33/505; H01L 25/0753; F21K 9/68; G02B 5/22; G02B 5/003; G02B 5/26
See application file for complete search history.

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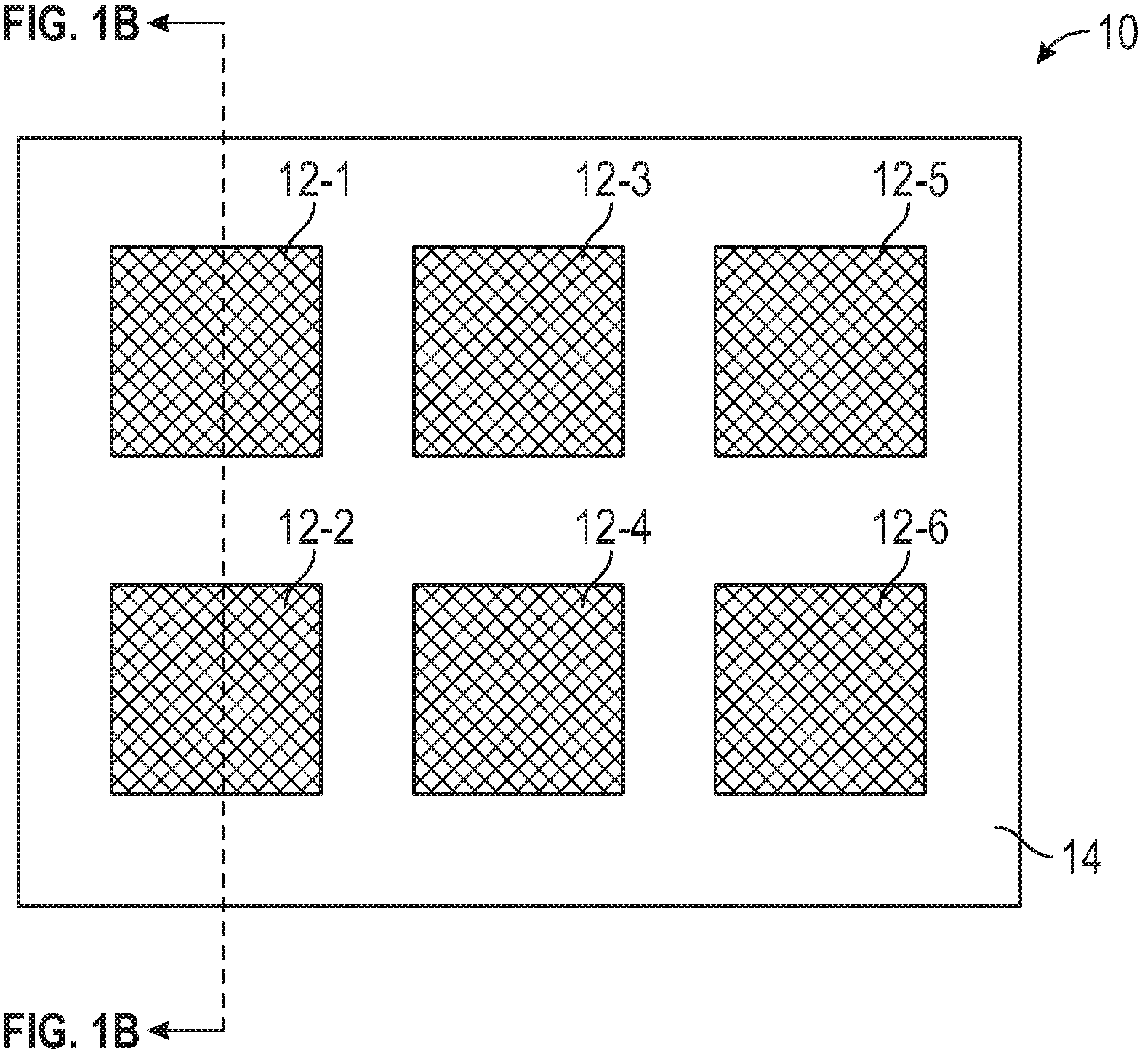
FIG. 1B
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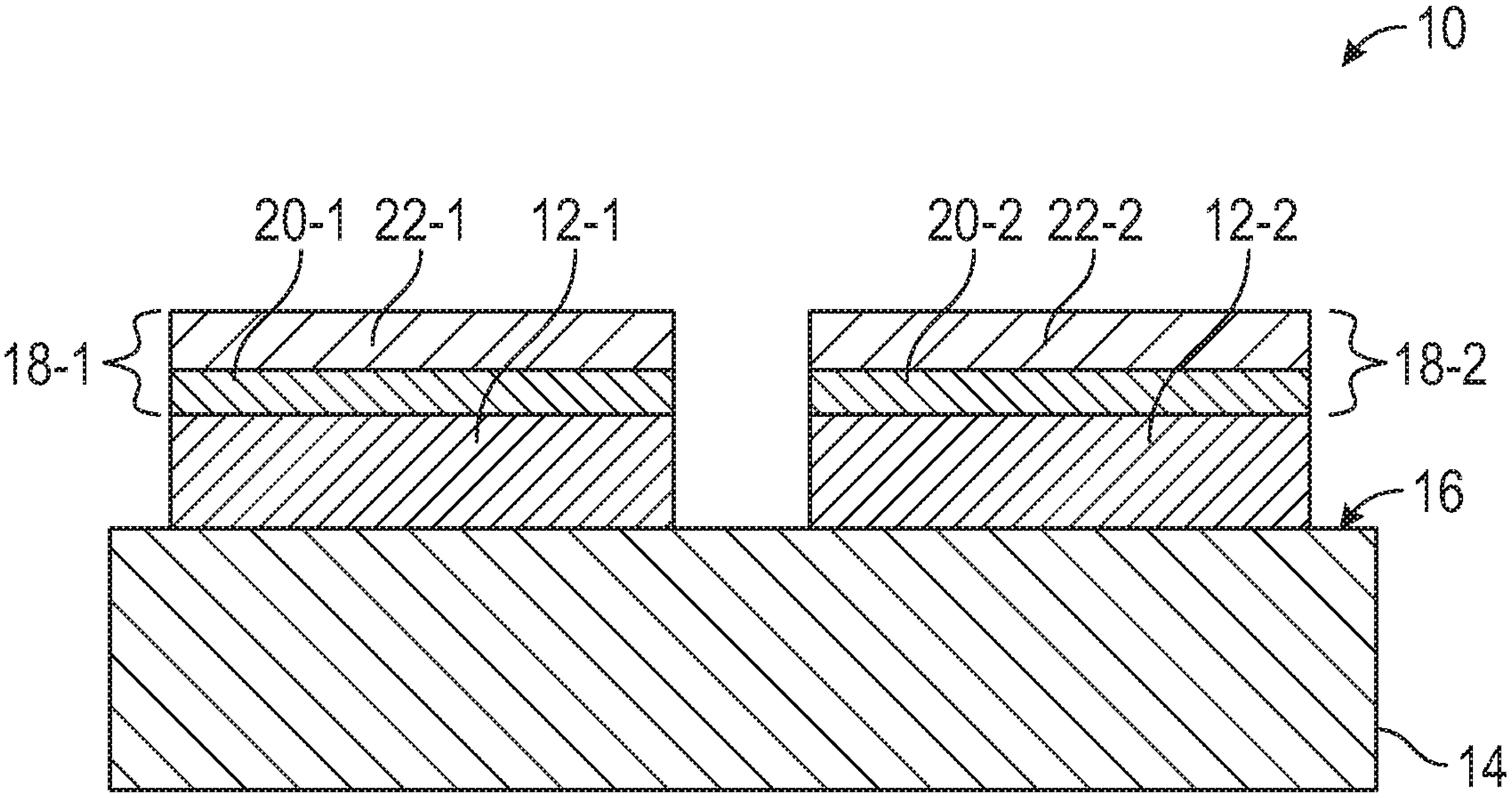
FIG. 1B

FIG. 1A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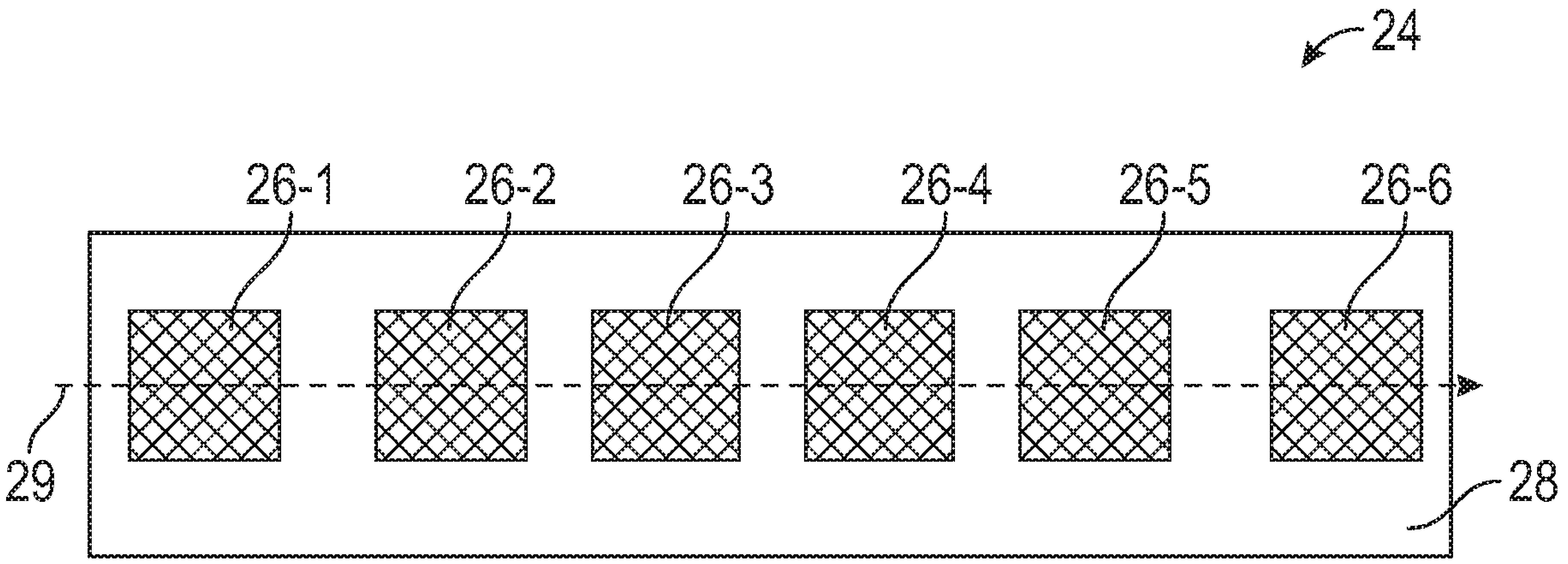
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FIG. 2A

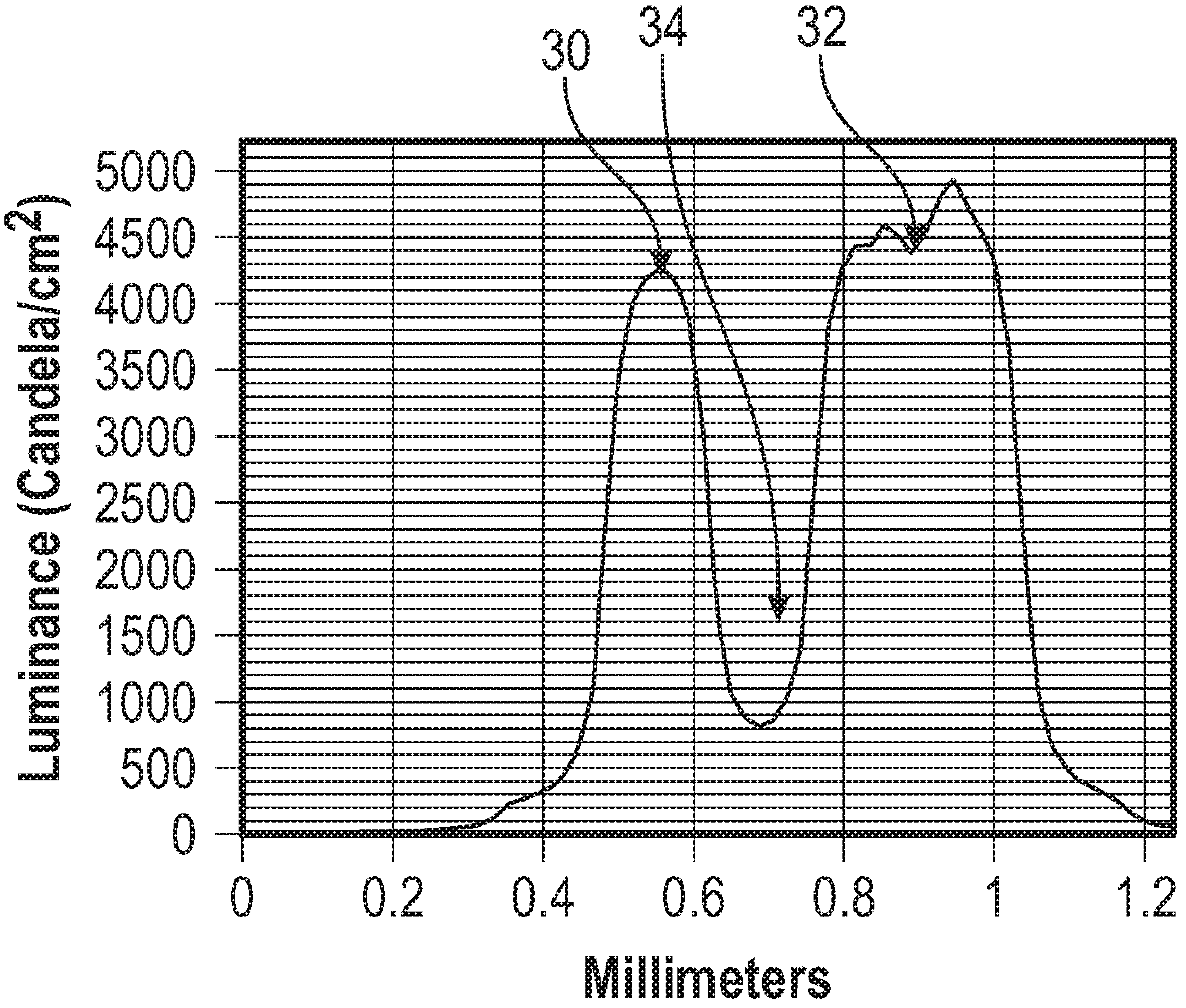
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FIG. 2B

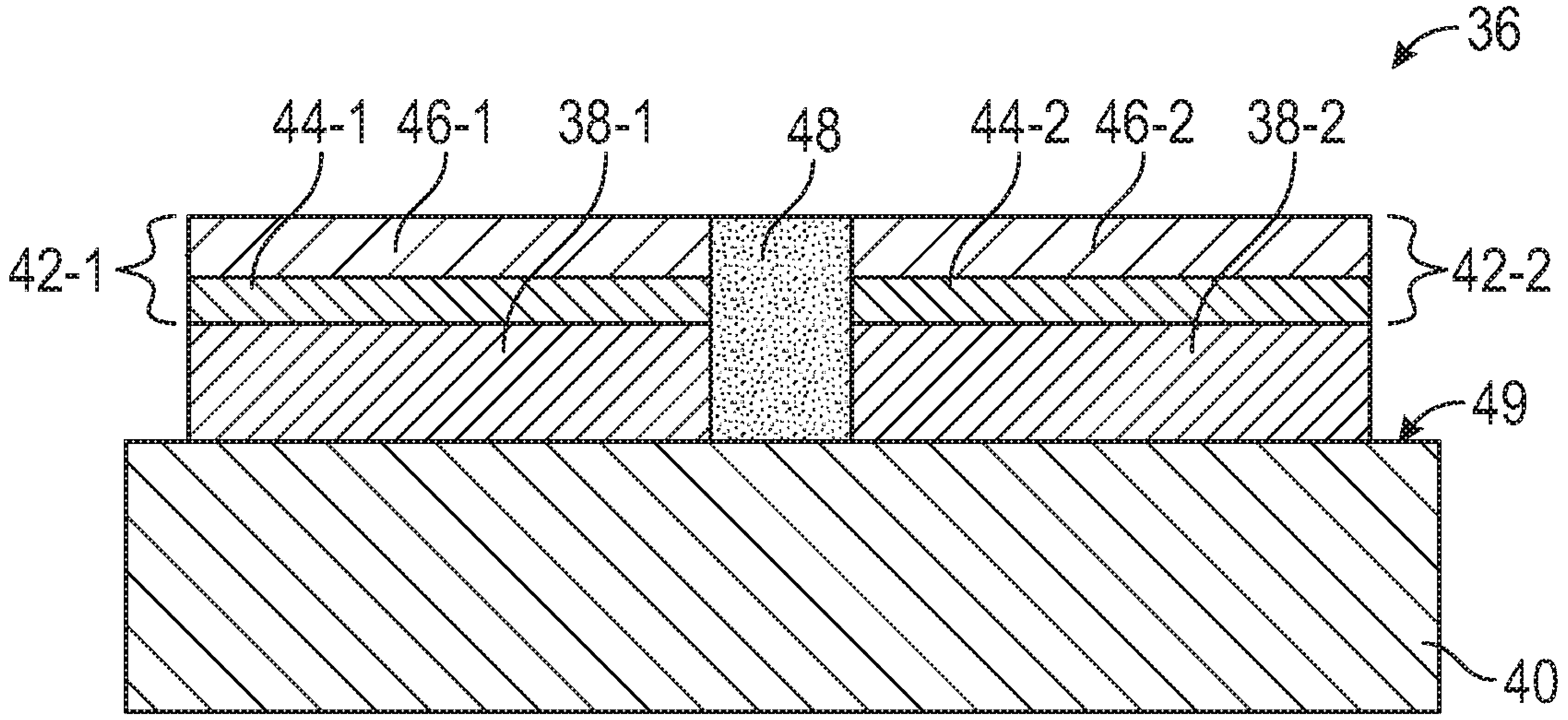
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FIG. 3A

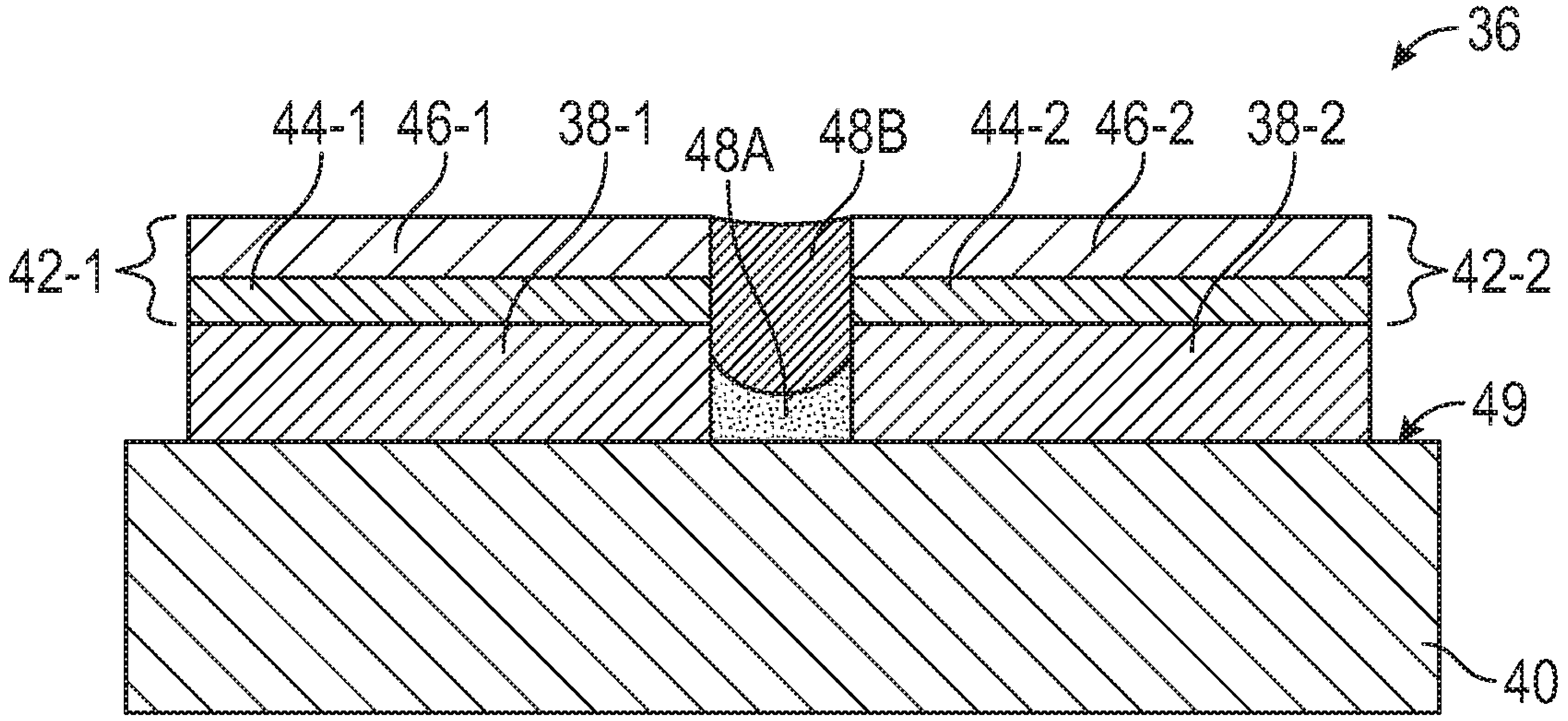
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FIG. 3B

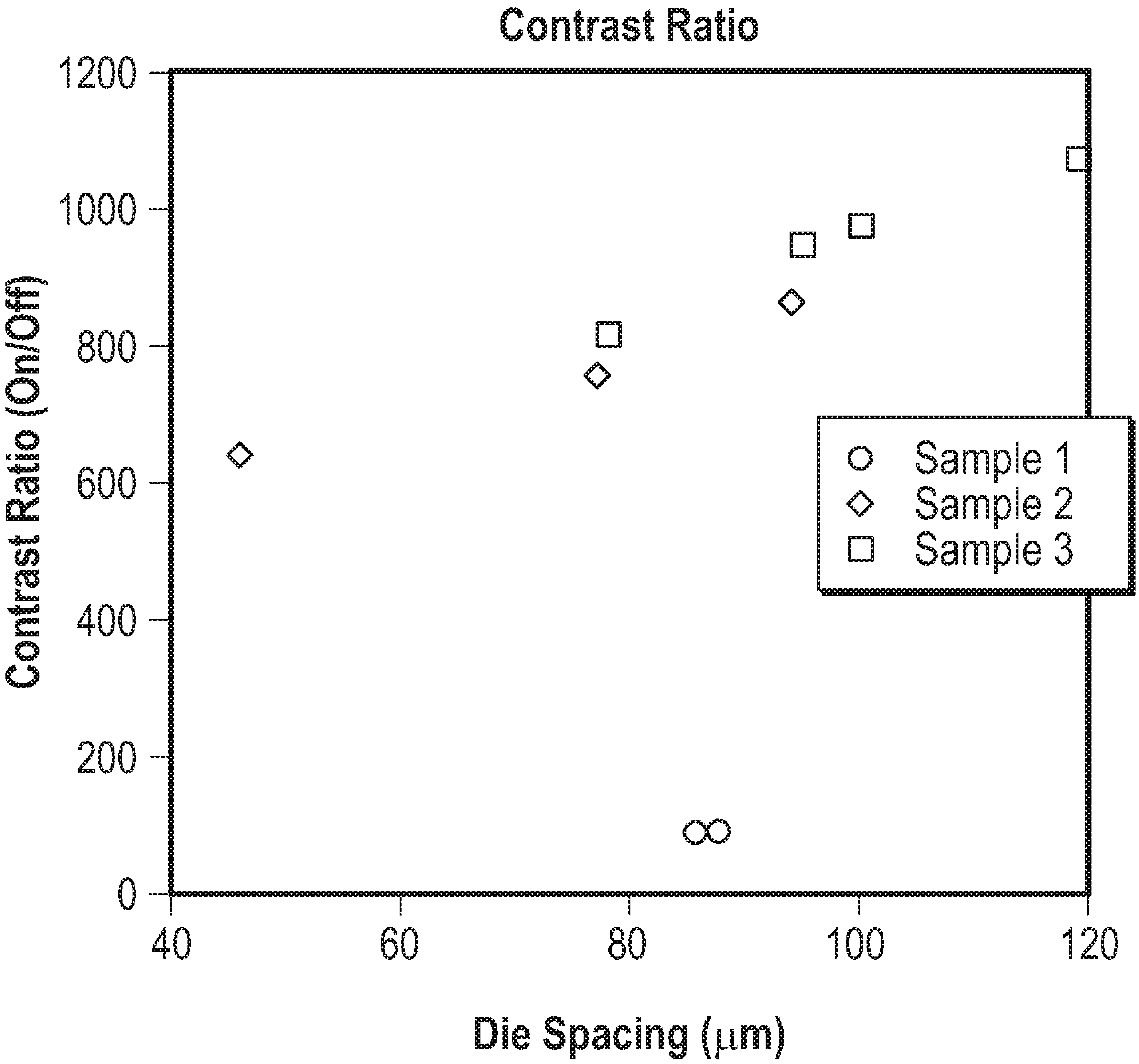
Contrast Ratio
1200
1000
800
600
400
200
0
Contrast Ratio (On/Off)
40
60
80
100
120
Die Spacing (μm)
○ Sample 1
◇ Sample 2
□ Sample 3

FIG. 3C

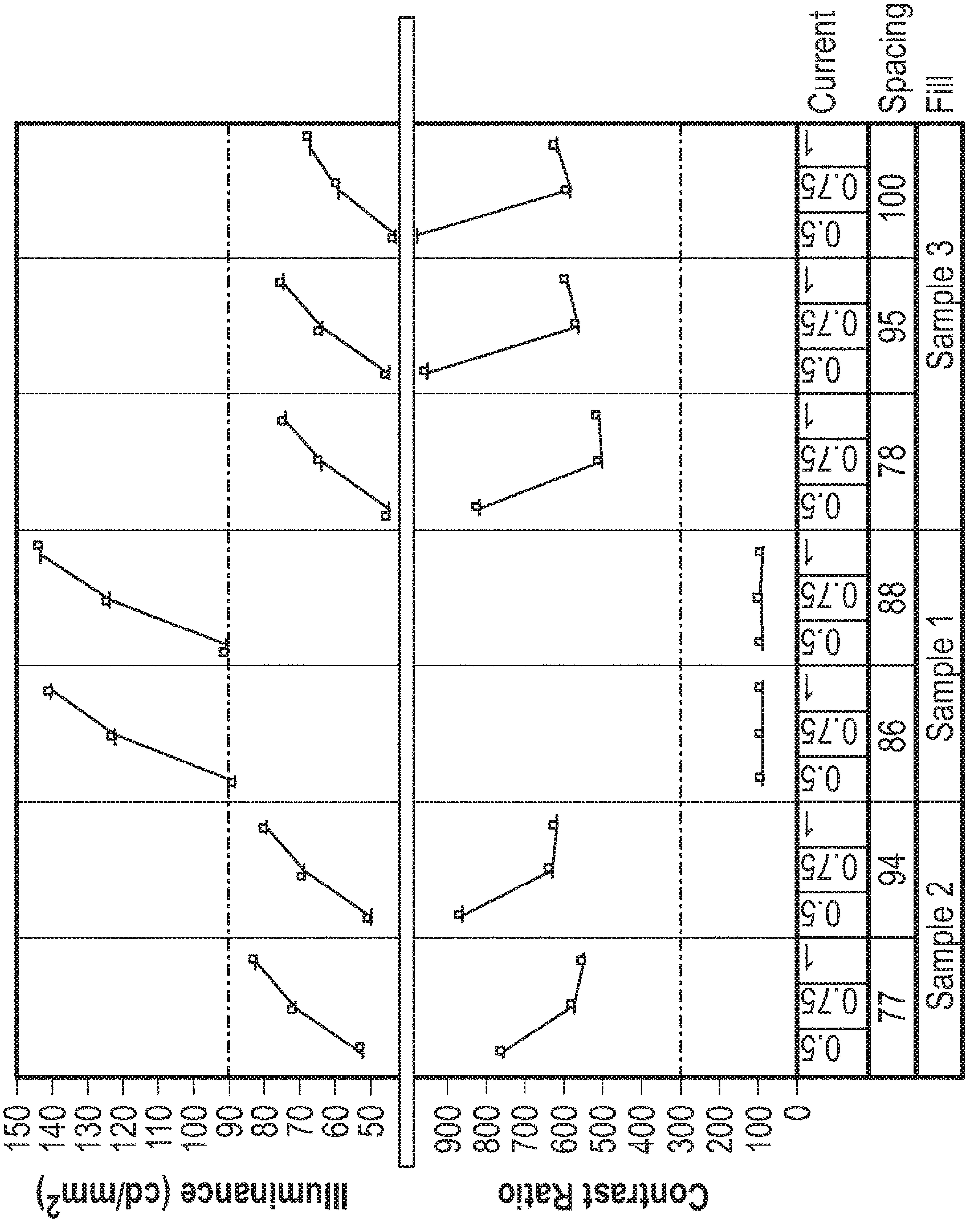
Illuminance (cd/mm²)
150
140
130
120
110
100
90
80
70
60
50
Contrast Ratio
900
800
700
600
500
400
300
200
100
0
Current
Spacing
Fill
0.5
0.75
1
77
94
86
88
78
95
100
Sample 2
Sample 1
Sample 3

FIG. 4

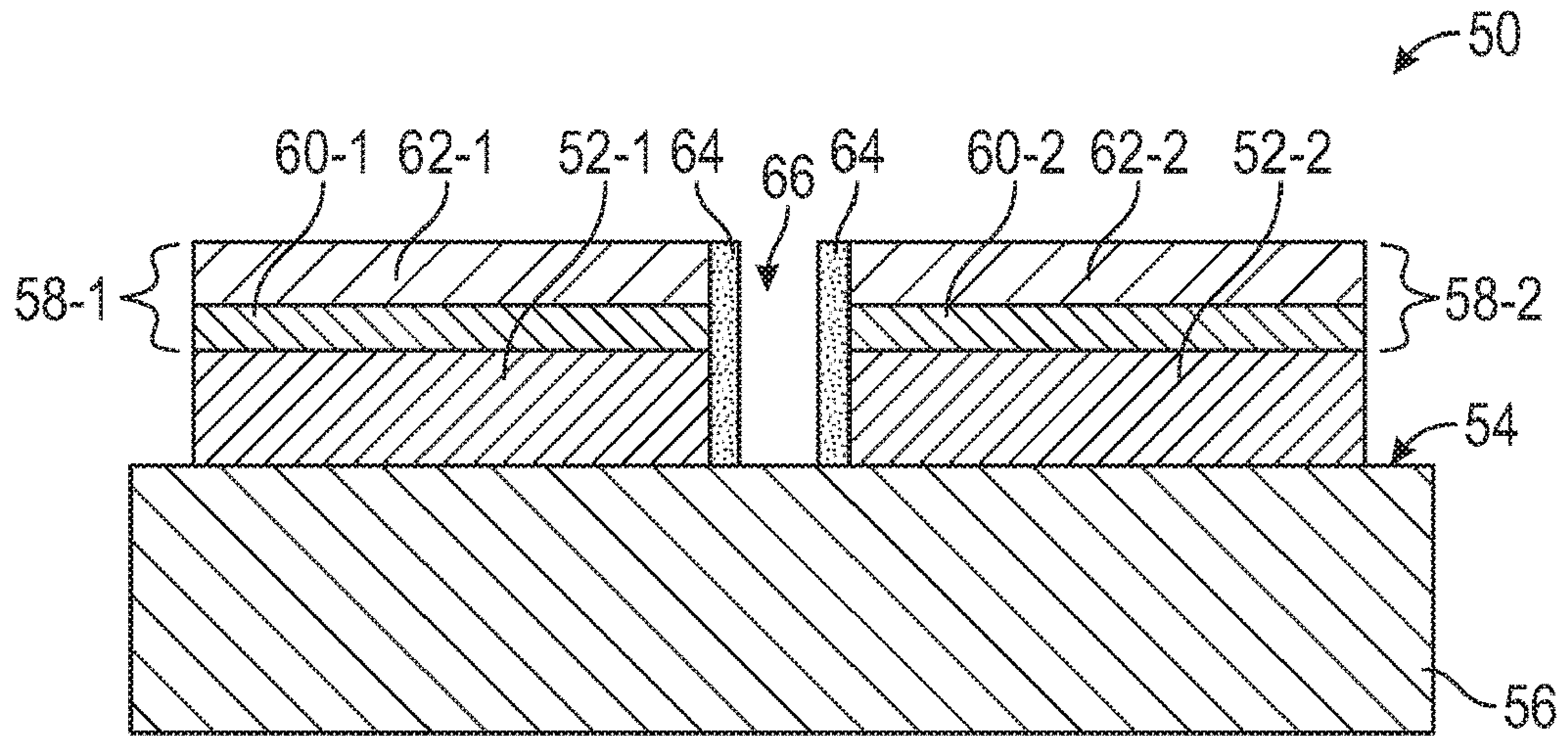

FIG. 5

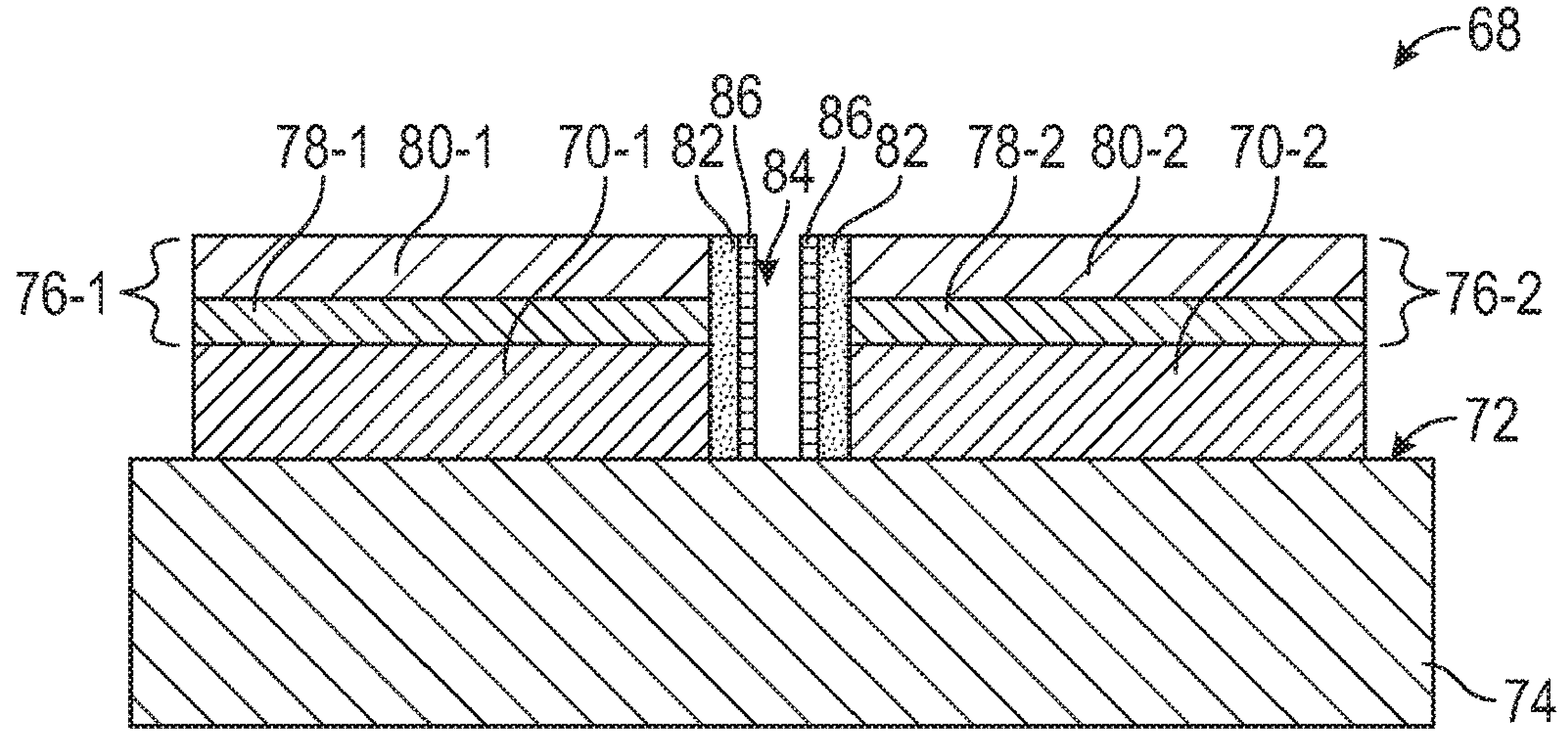

FIG. 6

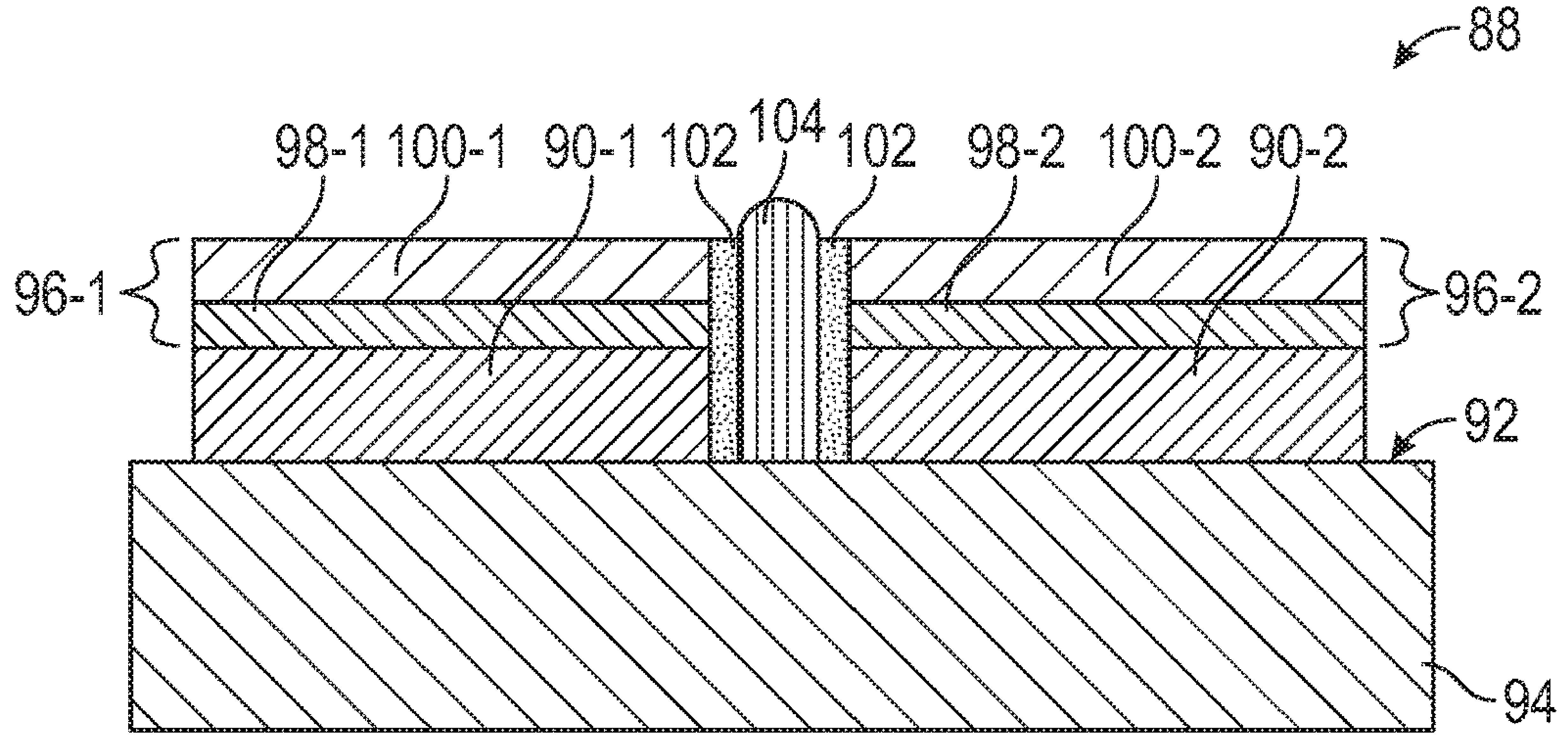

FIG. 7

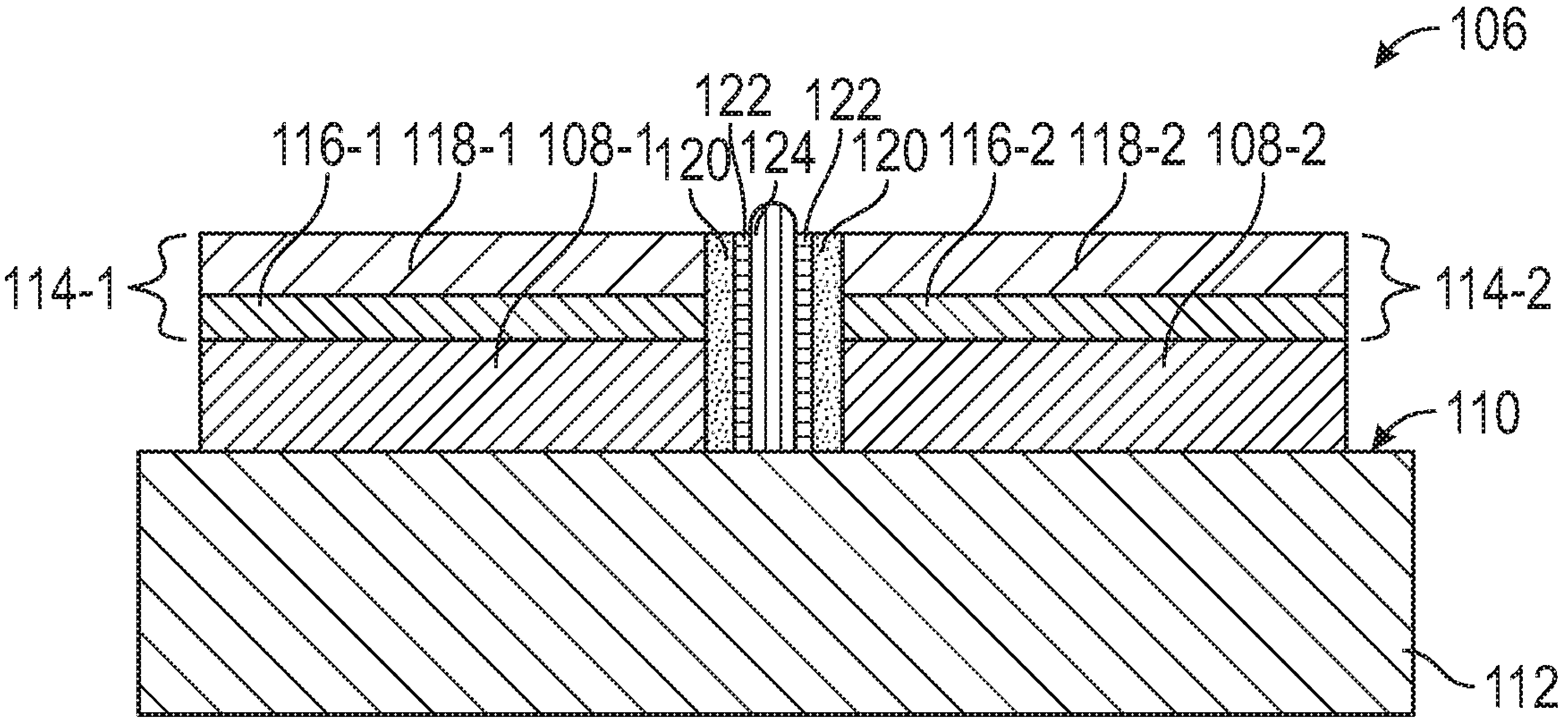
106
122
122
116-1
118-1
108-1
120
124
120
116-2
118-2
108-2
114-1
114-2
110
112

FIG. 8

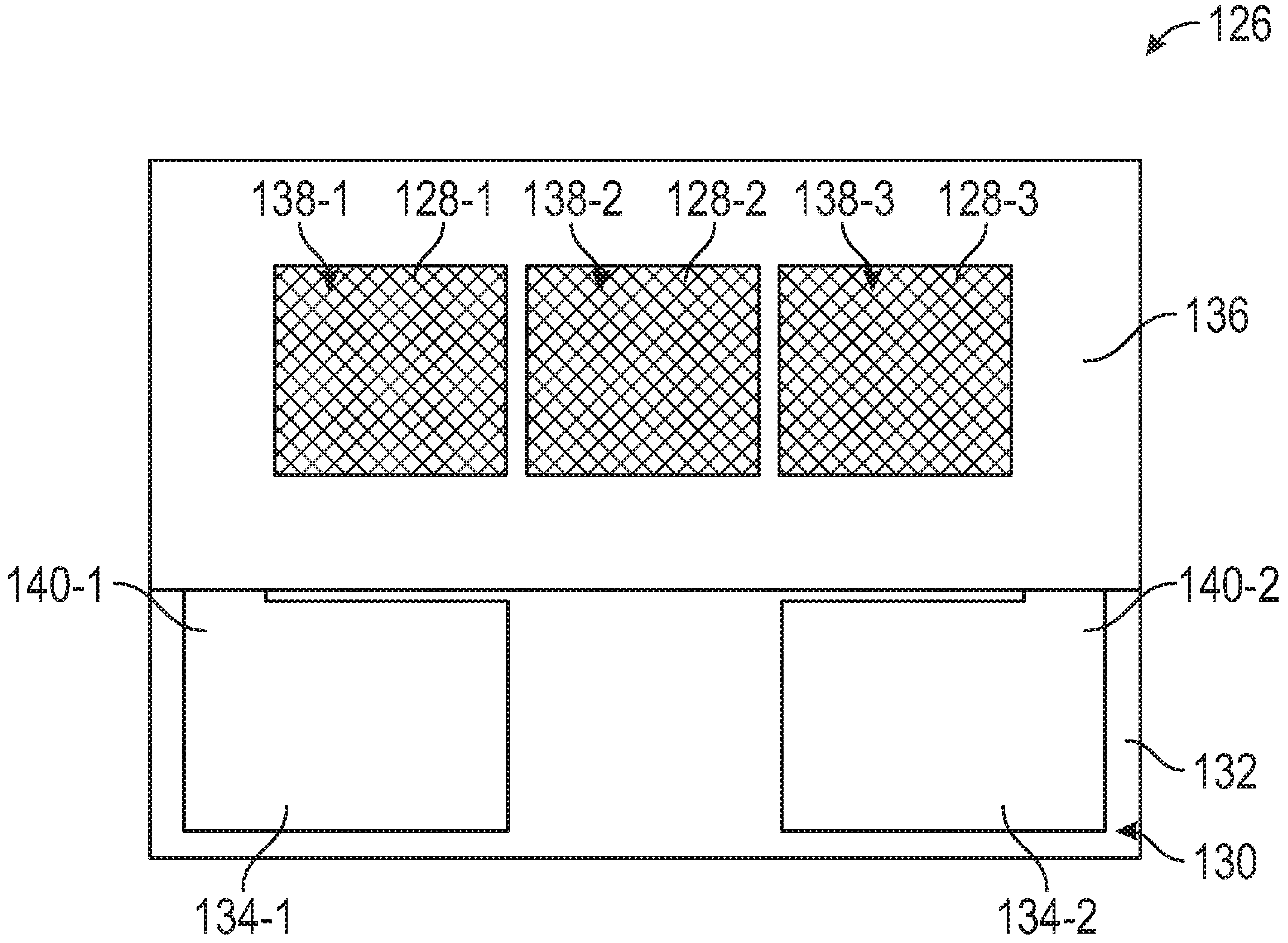
126
138-1
128-1
138-2
128-2
138-3
128-3
136
140-1
140-2
132
130
134-1
134-2

FIG. 9

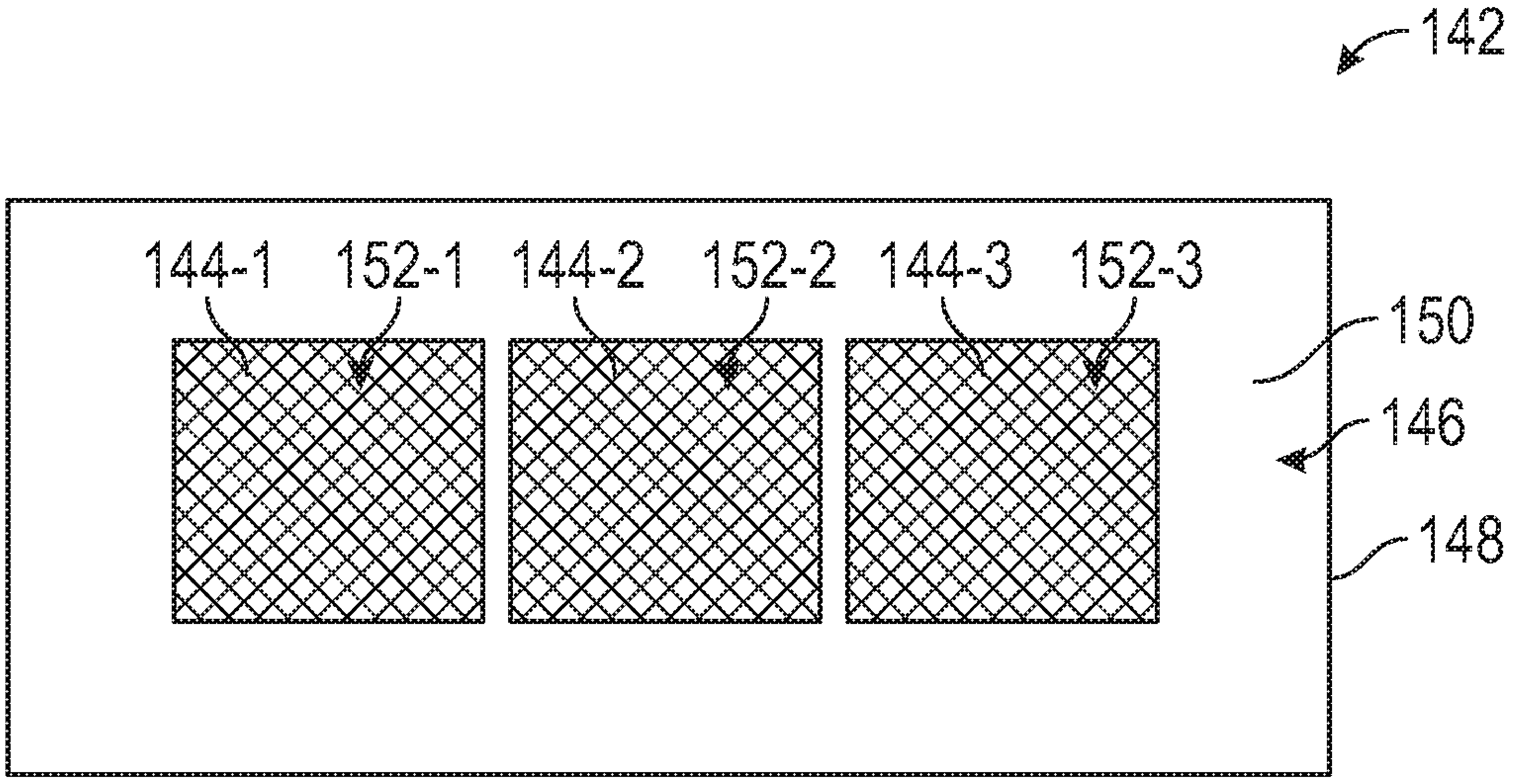

FIG. 10A

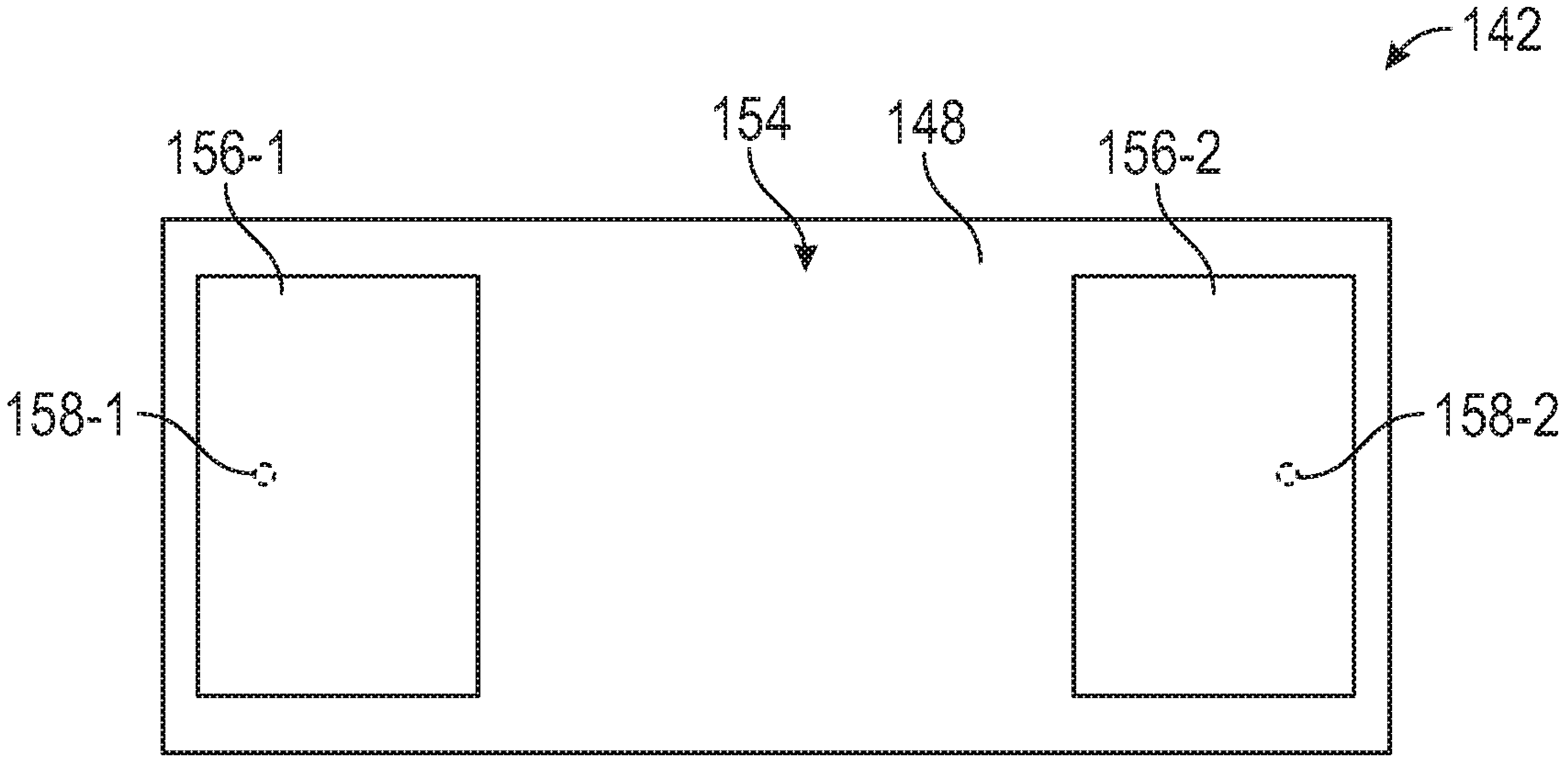

FIG. 10B

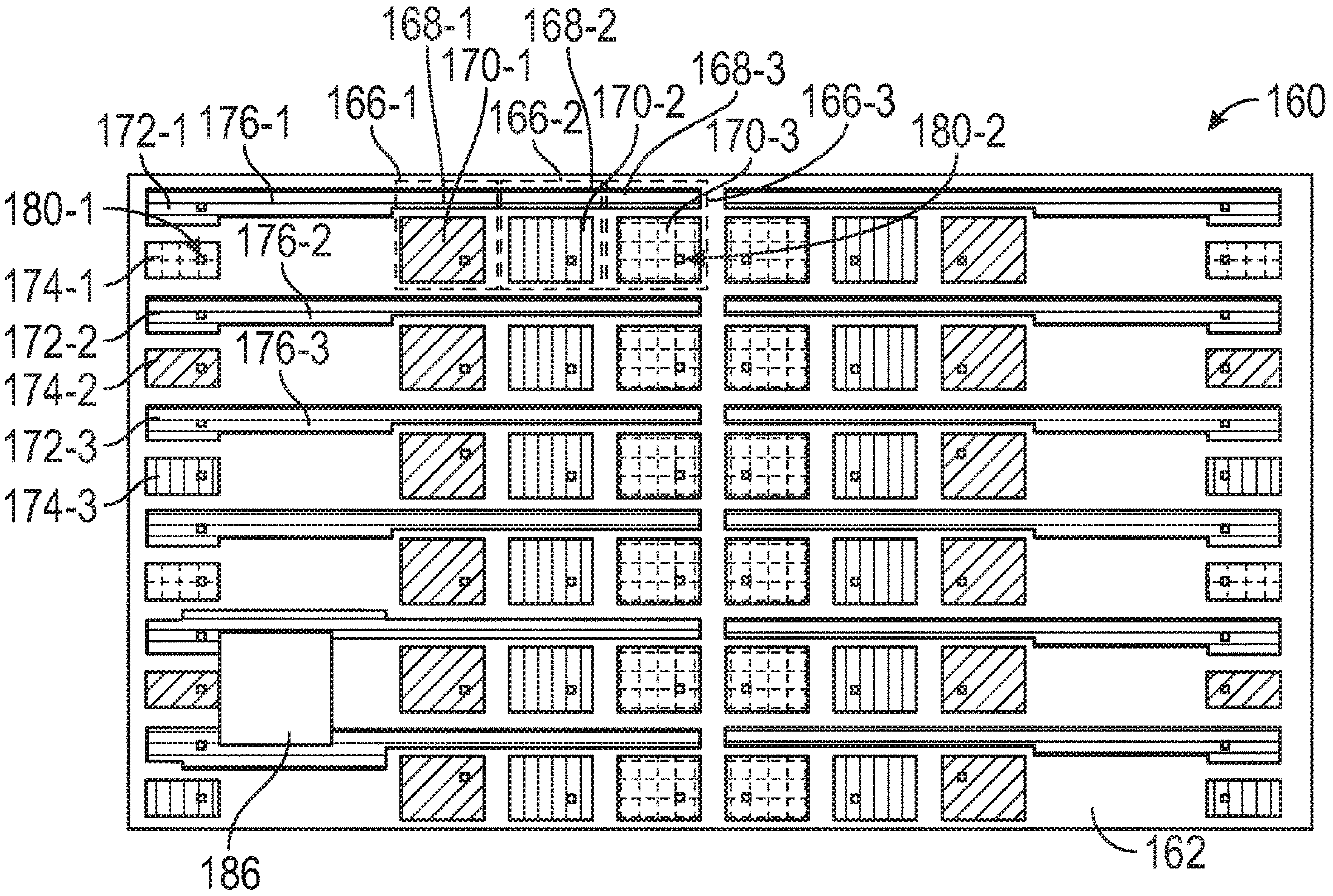

FIG. 11A

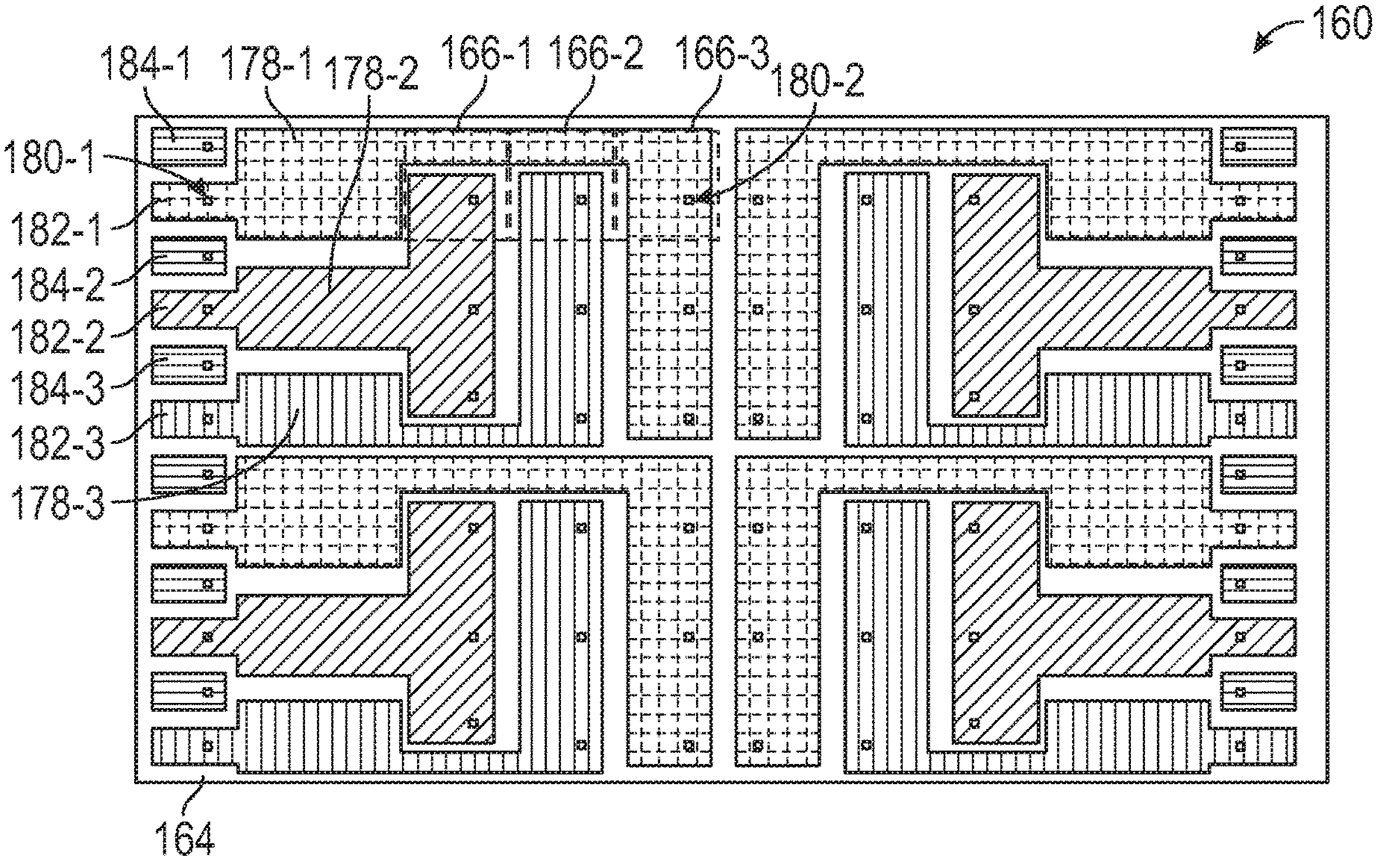

FIG. 11B

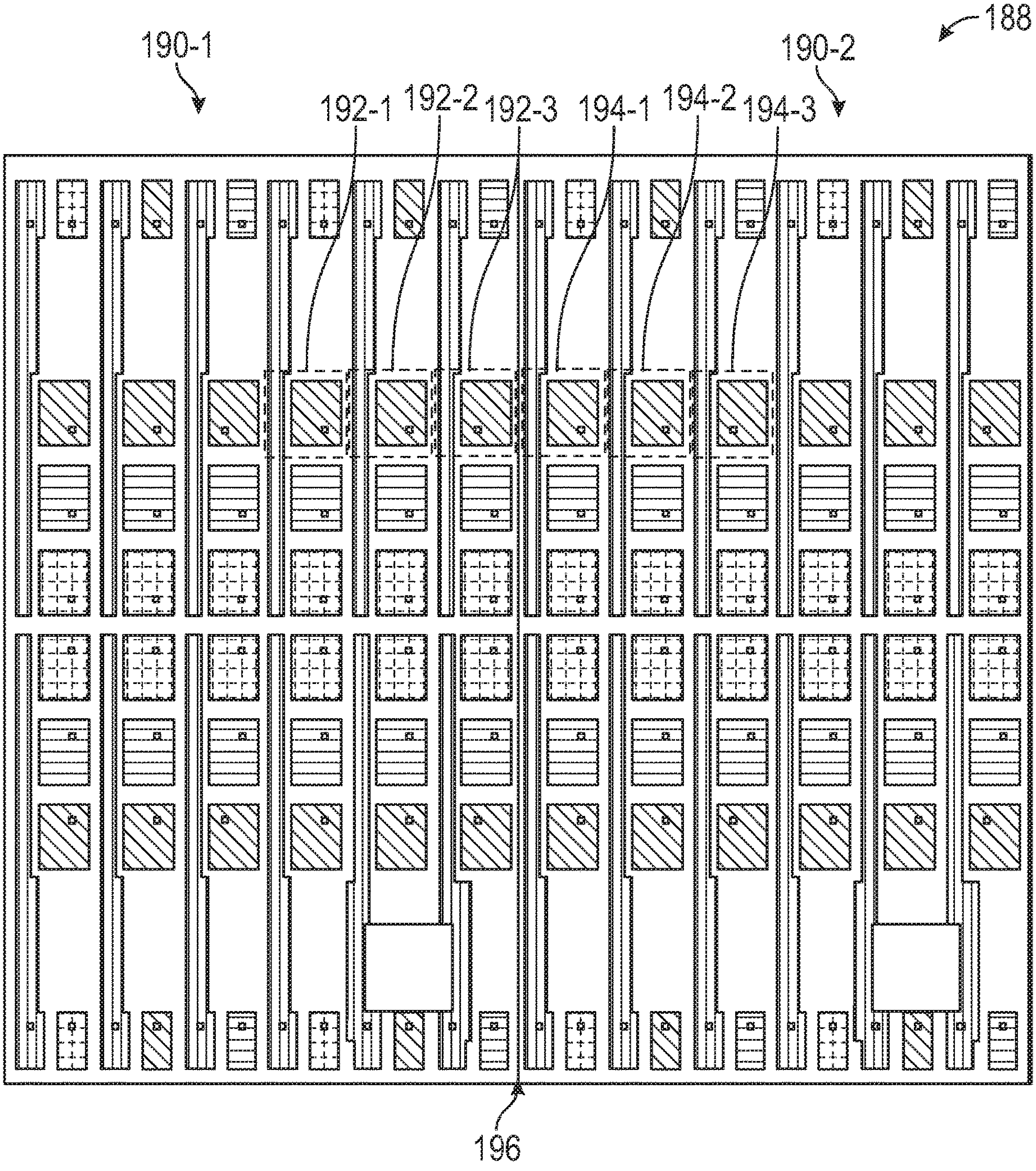

FIG. 12

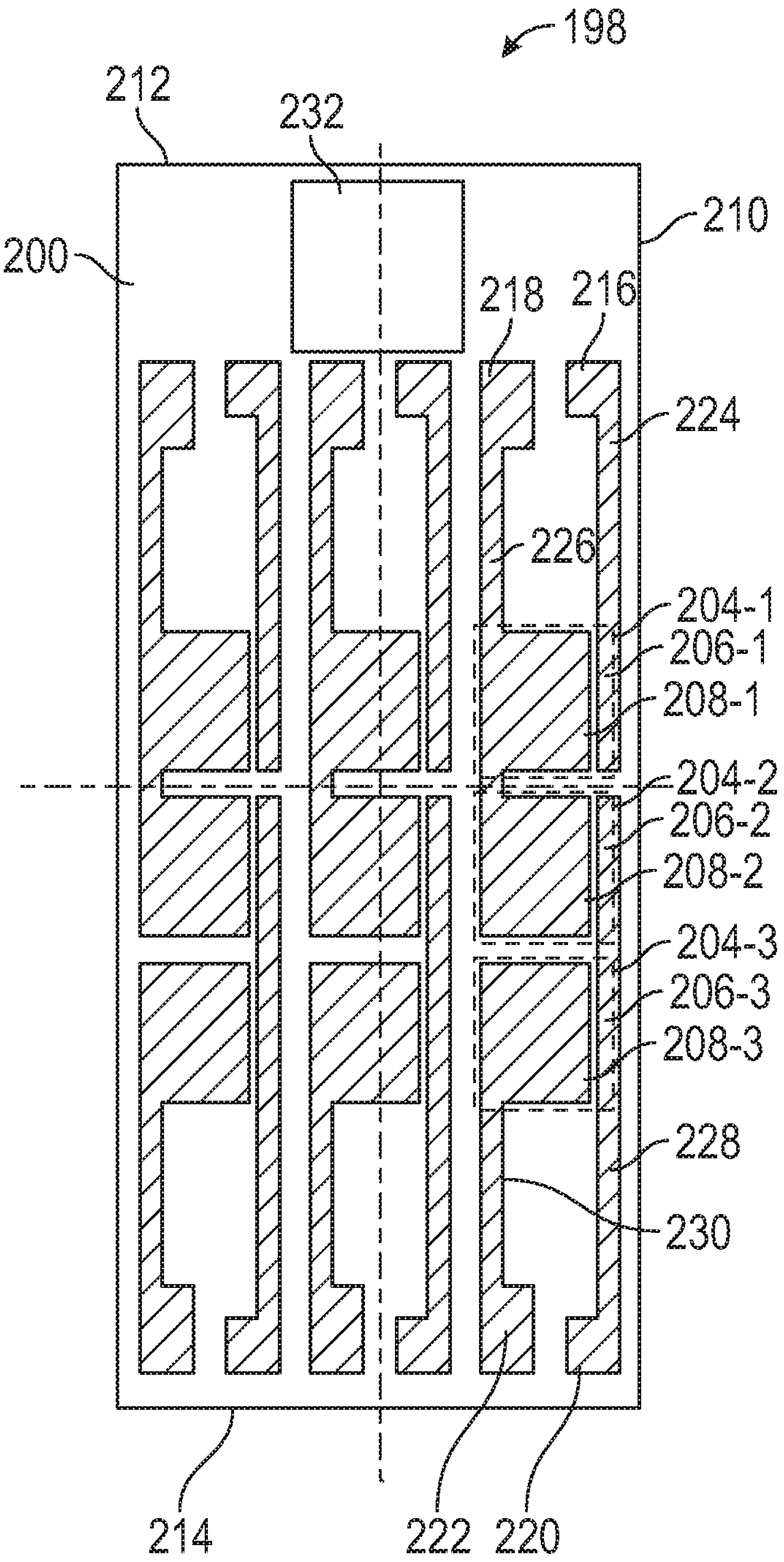

FIG. 13A

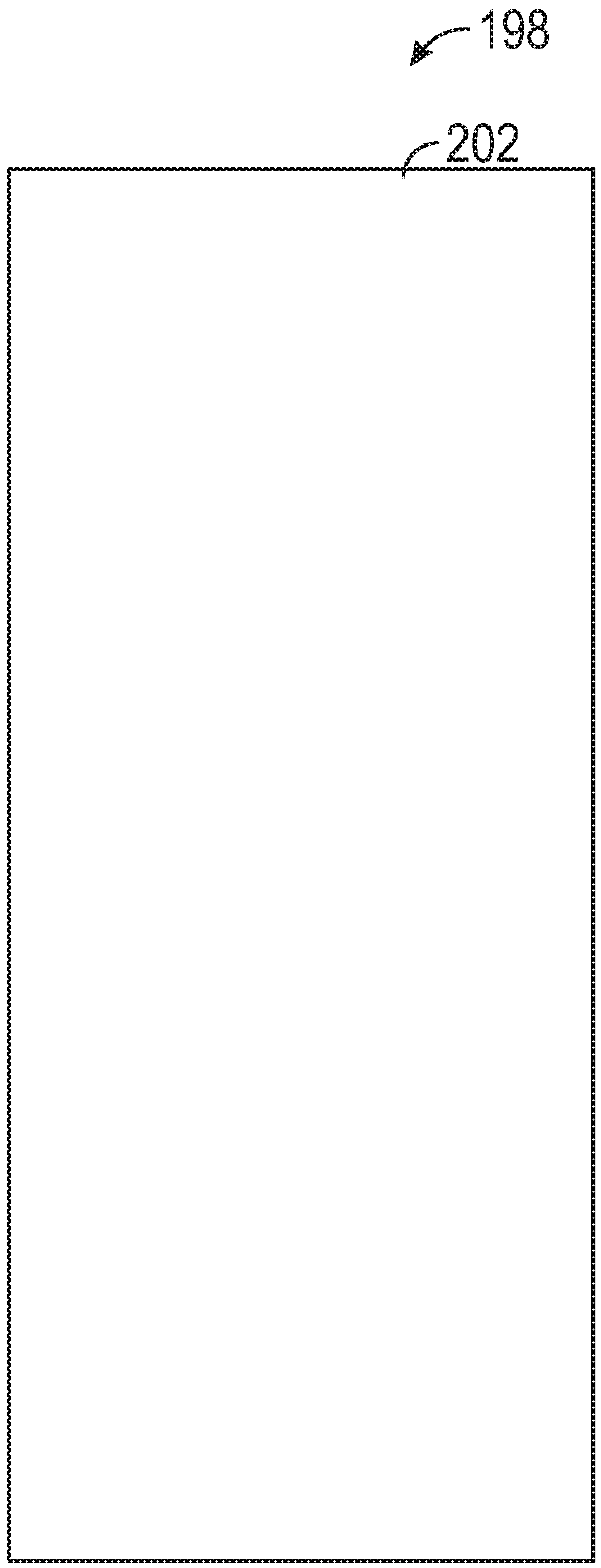

FIG. 13B

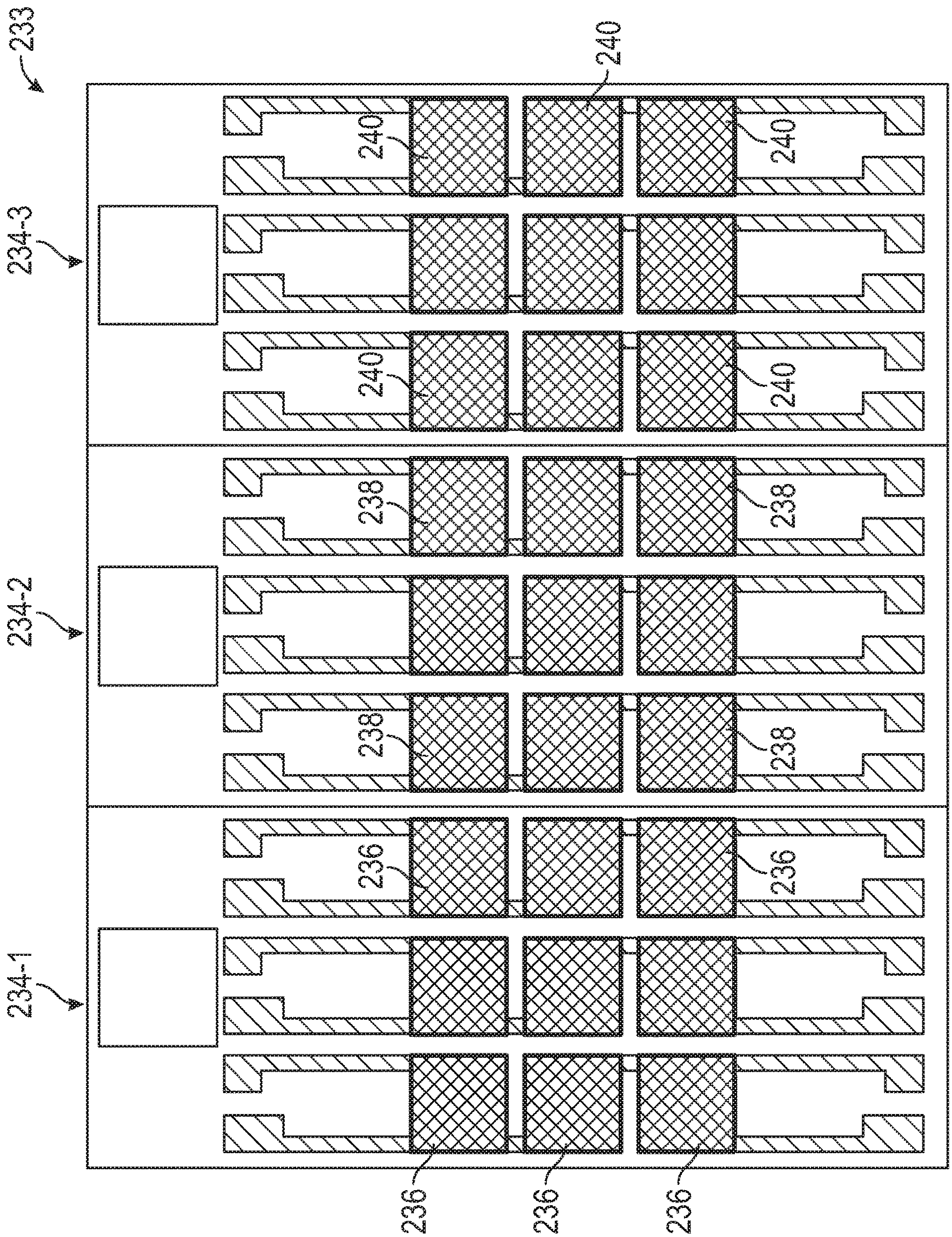
233
234-1
234-2
234-3
236
236
236
236
236
238
238
238
238
240
240
240
240
240

FIG. 14

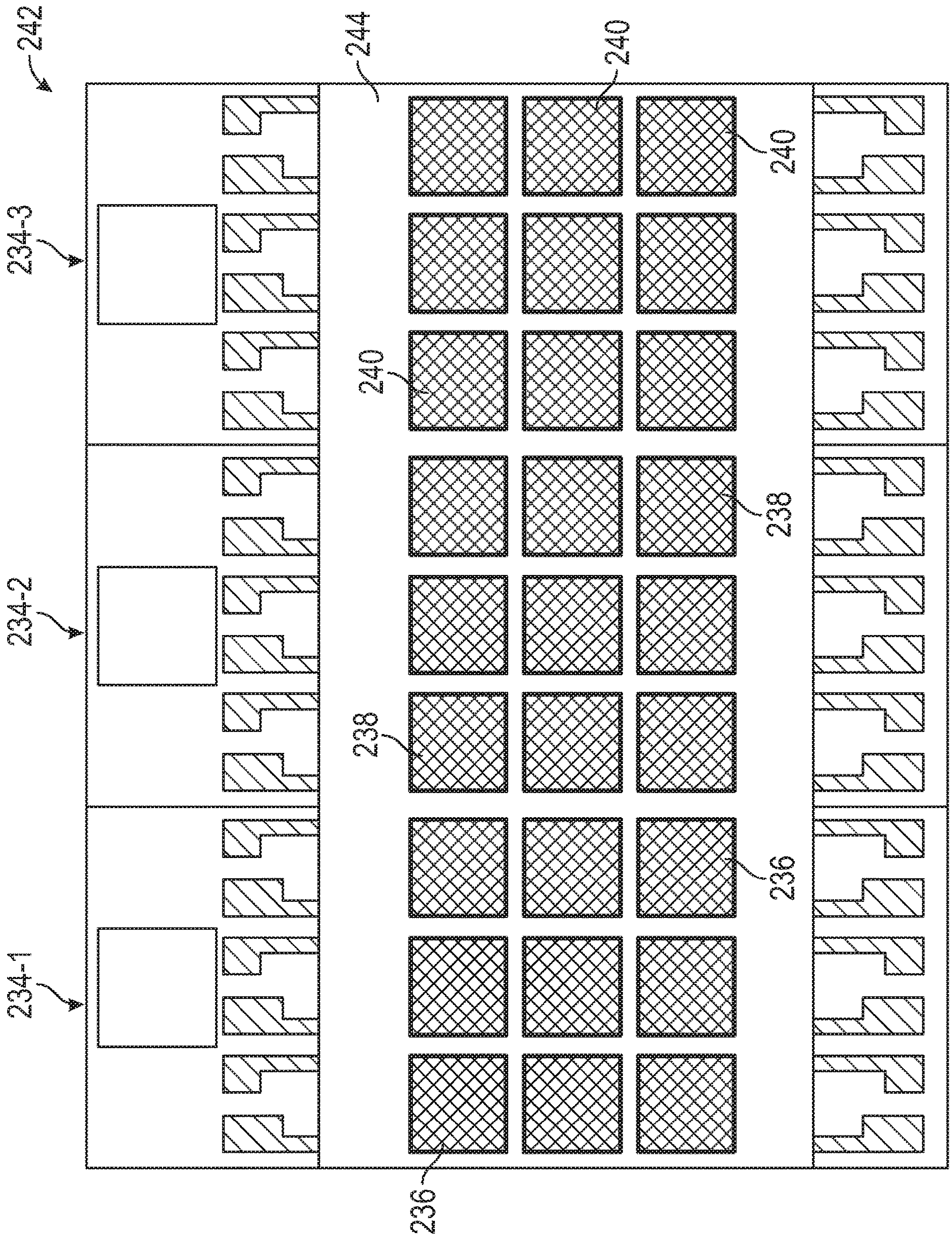

FIG. 15

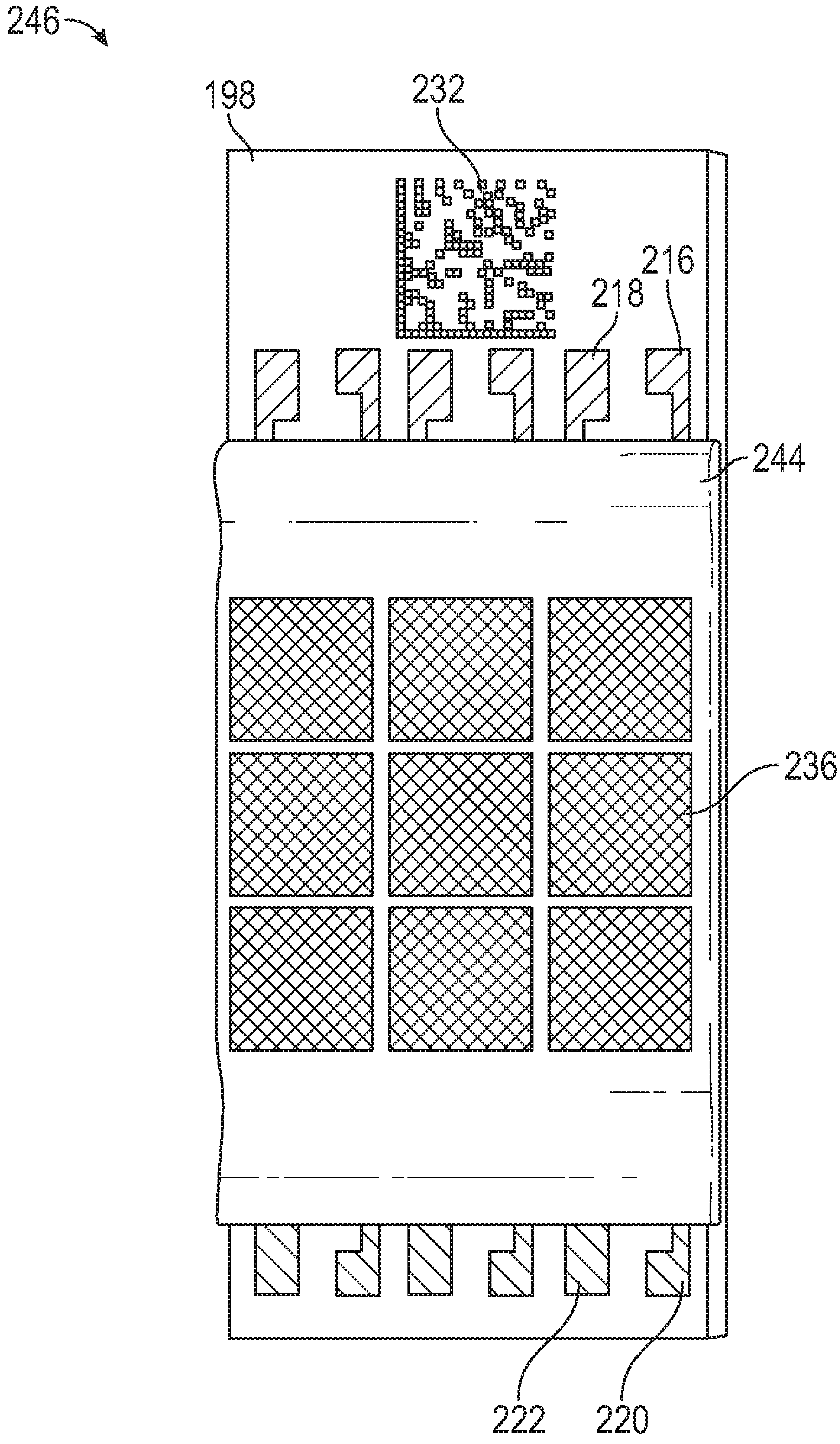

FIG. 16

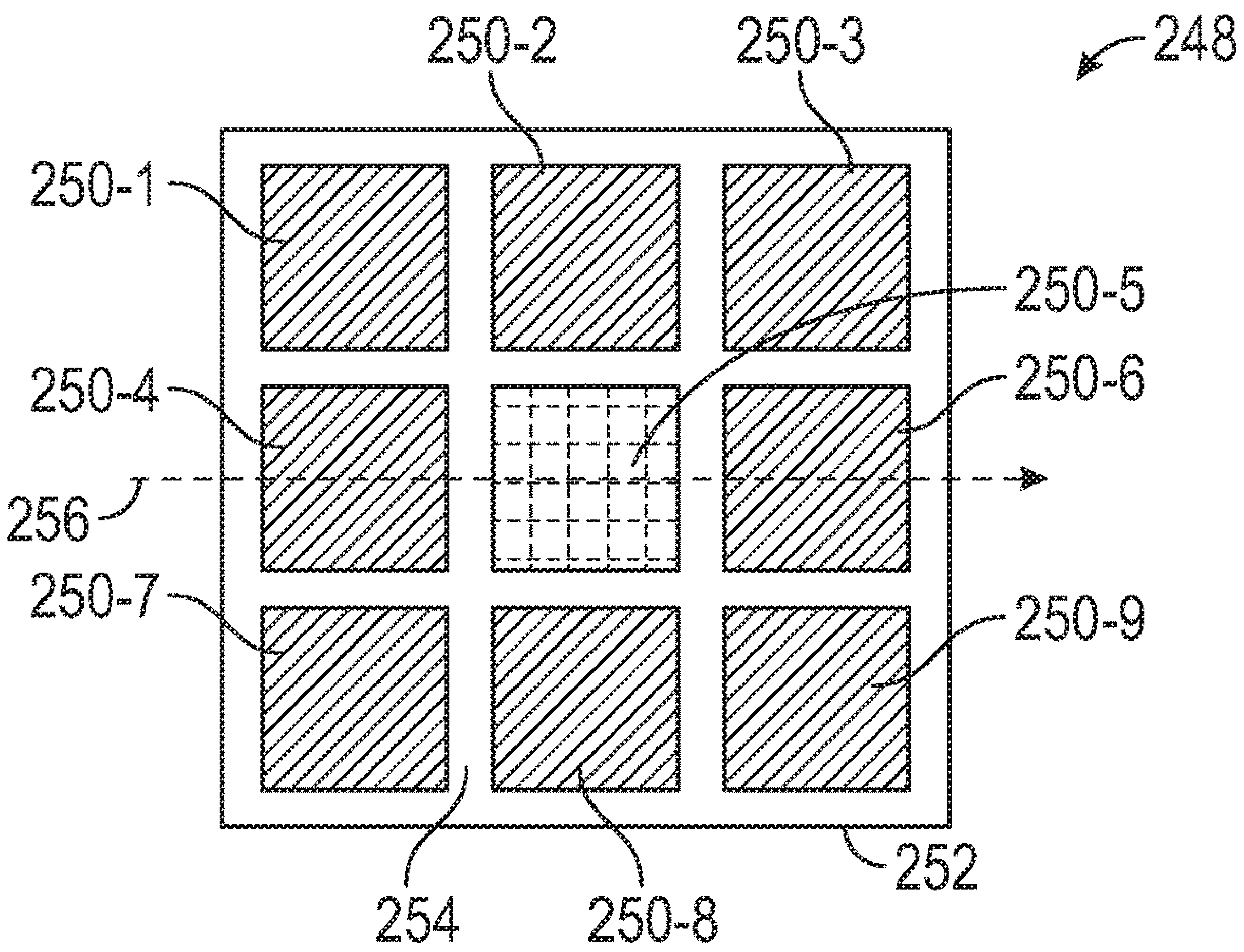

FIG. 17A

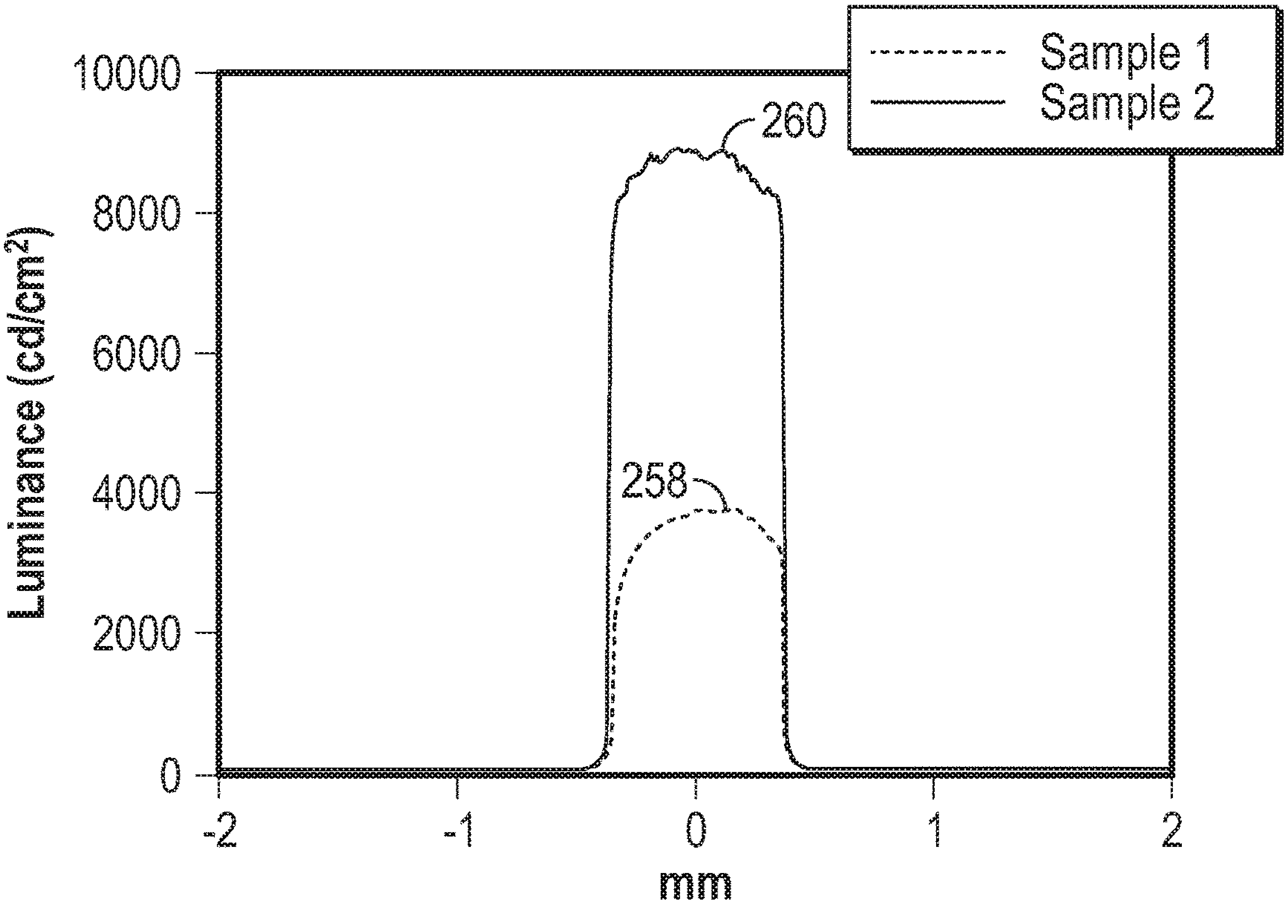

FIG. 17B

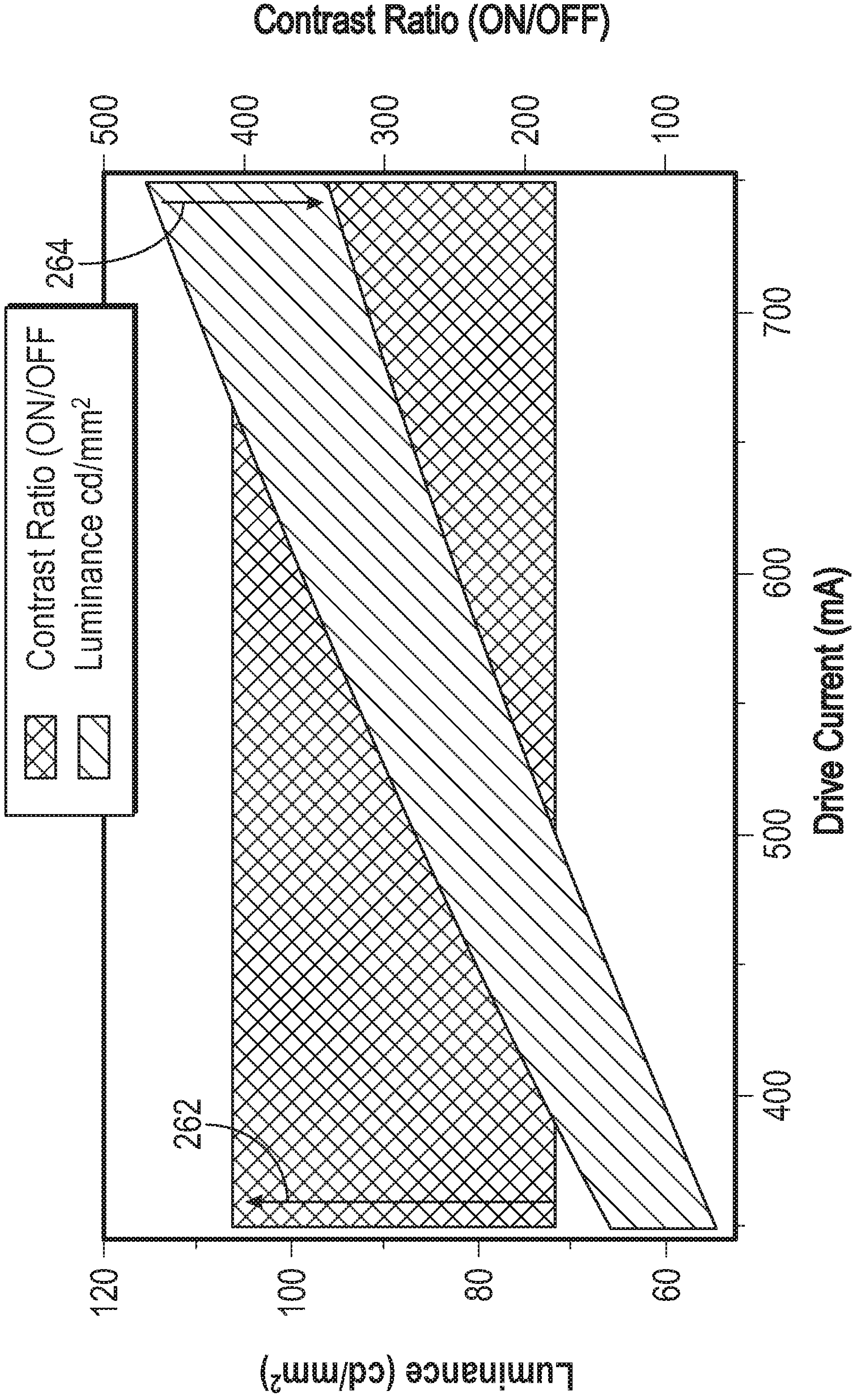
Contrast Ratio (ON/OFF)
500
400
300
200
100
264
Contrast Ratio (ON/OFF
Luminance cd/mm^2
262
120
100
80
60
Luminance (cd/mm^2)
400
500
600
700
Drive Current (mA)

FIG. 18

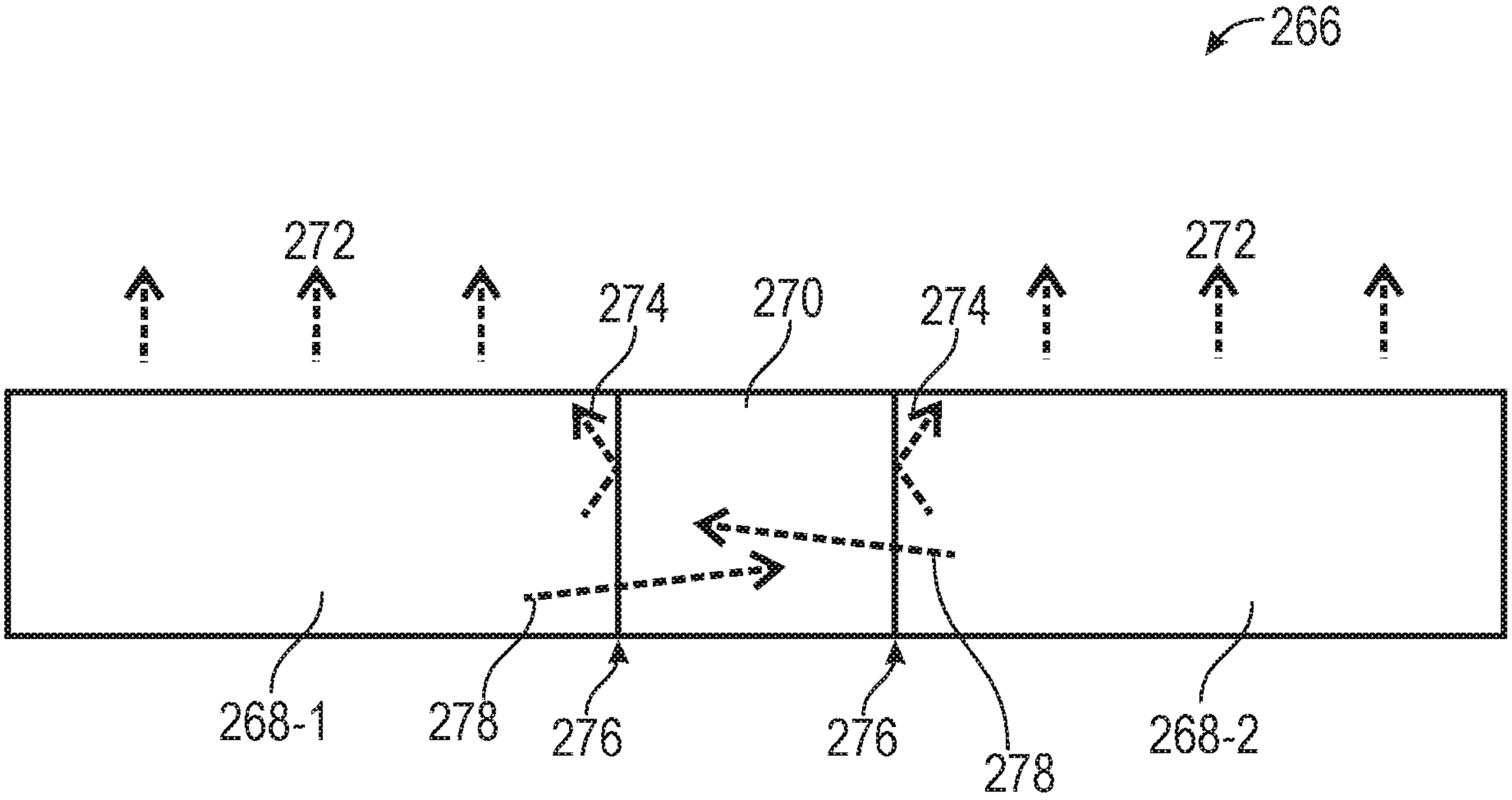

FIG. 19A

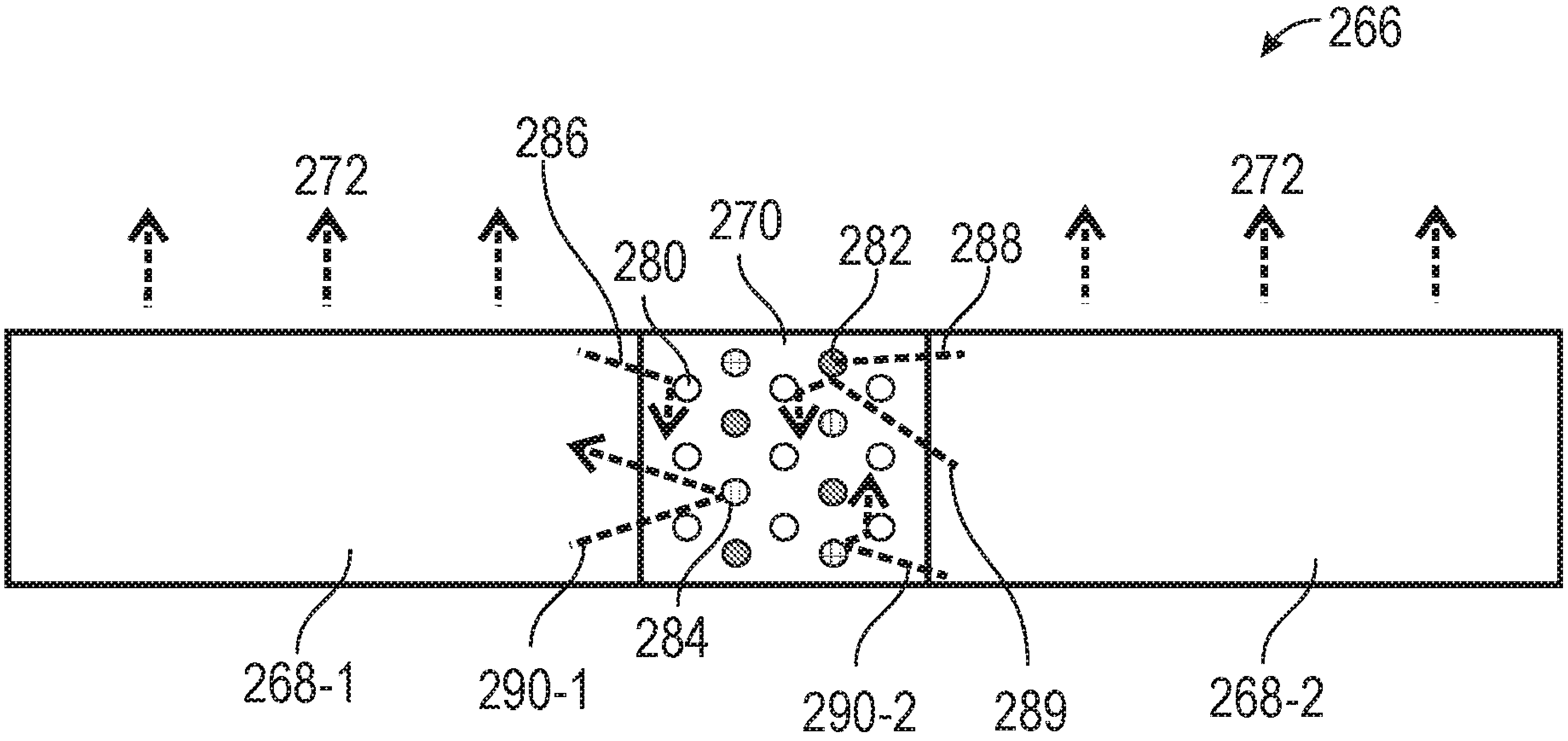

FIG. 19B

LIGHT-EMITTING DIODES, LIGHT-EMITTING DIODE ARRAYS AND RELATED DEVICES

RELATED APPLICATIONS

This application claims priority to provisional patent application Ser. No. 62/755,076, filed on Nov. 2, 2018, and is a continuation-in-part of U.S. patent application Ser. No. 16/118,779, filed on Aug. 31, 2018, entitled "LIGHT-EMITTING DIODES, LIGHT-EMITTING DIODE ARRAYS AND RELATED DEVICES," the disclosures of which are hereby incorporated herein by reference in their entireties.

FIELD OF THE DISCLOSURE

The present disclosure relates to solid-state lighting devices including light-emitting diodes, light-emitting diode arrays, and devices incorporating light-emitting diodes or light-emitting diode arrays.

BACKGROUND

Solid-state lighting devices such as light-emitting diodes (LEDs) are increasingly used in both consumer and commercial applications. Advancements in LED technology have resulted in highly efficient and mechanically robust light sources with a long service life. Accordingly, modern LEDs have enabled a variety of new display applications and are being increasingly utilized for general illumination applications, often replacing incandescent and fluorescent light sources.

LEDs are solid-state devices that convert electrical energy to light and generally include one or more active layers of semiconductor material (or an active region) arranged between oppositely doped n-type and p-type layers. When a bias is applied across the doped layers, holes and electrons are injected into the one or more active layers where they recombine to generate emissions such as visible light or ultraviolet emissions. An LED chip typically includes an active region that may be fabricated, for example, from silicon carbide, gallium nitride, gallium phosphide, aluminum nitride, gallium arsenide-based materials, and/or from organic semiconductor materials. Photons generated by the active region are initiated in all directions.

LEDs have been widely adopted in various illumination contexts, for backlighting of liquid crystal display (LCD) systems (e.g., as a substitute for cold cathode fluorescent lamps), and for sequentially illuminated LED displays. Applications utilizing LED arrays include vehicular headlamps, roadway illumination, light fixtures, and various indoor, outdoor, and specialty contexts. Desirable characteristics of LED devices include high luminous efficacy, long lifetime, and wide color gamut. In such LED array applications, it may be desirable to have LEDs spaced more closely together in order for the array to appear as a uniform emission area when all LEDs are electrically activated, or turned on. However, when some LEDs of the LED array are turned off, or electrically deactivated, it may be challenging to provide good contrast between LEDs in an on-state relative to LEDs in an off-state. This is due in part to the omnidirectional character of LED emissions, which can make it difficult to prevent emissions of one LED from significantly overlapping with emissions of another LED of an array, thereby resulting in crosstalk or light spillage between emissions of adjacent LEDs. Significant overlap between beams emitted by adjacent LEDs tends to impair the effective resolution of a LED array device; however, attempts to segregate light beams may result in undesirable non-illuminated or "dark" zones between adjacent LEDs, and may also impair brightness of aggregate emissions. It may be challenging to provide LED array devices that address the foregoing issues in combination.

The art continues to seek improved LEDs and solid-state lighting devices having reduced optical losses and providing desirable illumination characteristics capable of overcoming challenges associated with conventional lighting devices.

SUMMARY

Aspects disclosed herein relate to light-emitting diodes (LEDs), LED arrays, and related devices. An LED device includes a first LED chip and a second LED chip mounted on a submount with a light-altering material between the first LED chip and the second LED chip. The light-altering material may include at least one or more of a light-reflective material and a light-absorbing material. In certain embodiments, the light-altering material may include at least one of nanoparticles, nanowires, mesoparticles, mesowires, or combinations thereof. Individual wavelength conversion elements may be arranged on each of the first LED chip and the second LED chip. The light-altering material may improve contrast between the first LED chip and the second LED chip as well as between the individual wavelength conversion elements. LED devices may include submounts with at least one electrically conductive anode or cathode path that is discontinuous on a surface of the submount where LED chips are mounted. LED devices may include submounts in modular configurations where LED chips may be mounted on adjacent submounts to form an LED array. Each LED chip of the LED array may be laterally separated from at least one other LED chip by a same distance, and a light-altering material may be arranged around the LED array.

In one aspect, an LED device comprises: a submount; a first LED chip on a surface of the submount; a first light-altering material arranged around a perimeter of the first LED chip, wherein the first light-altering material comprises at least one of a plurality of nanowires or a plurality of mesowires in a binder. In certain embodiments, the plurality of nanowires comprises silicon nanowires or the plurality of mesowires comprises silicon mesowires. The first light-altering material may further comprise at least one of a nanopowder or a mesopowder. A total weight percent of the plurality of nanowires, the plurality of mesowires, the nanopowder, or the mesopowder may include a range of about greater than 0% to about 15% of a total weight of the first light-altering material. The first light-altering material may further comprise at least one of fused silica, fumed silica, titanium dioxide (TiO_2), or metal particles in the binder. In certain embodiments, the LED device may further comprise a first wavelength conversion element registered with the first LED chip, wherein the first wavelength conversion element comprises a first superstrate and a first lumiphoric material that is arranged between the first superstrate and the first LED chip. The first light-altering material may be further arranged around a perimeter of the first wavelength conversion element. In certain embodiments, the LED device may further comprise a second LED chip on the surface of the submount and wherein the first light-altering material is arranged between the first LED chip and the second LED chip.

In another aspect, an LED device comprises: a submount; a first LED chip and a second LED chip on a surface of the submount, wherein the first LED chip is laterally separated from the second LED chip on the surface; and a first light-altering material arranged between the first LED chip and the second LED chip on the submount, wherein the first light-altering material comprises a plurality of nanoparticles in a binder. In certain embodiments, the plurality of nanoparticles comprises silicon nanoparticles. The plurality of nanoparticles may comprise shapes including one or more combinations of wires, spheres, ovals, cubes, pyramids, and asymmetric shapes. A total weight percent of the plurality of nanoparticles may comprise a range of about greater than 0% to about 15% of a total weight of the first light-altering material. The first light-altering material may further comprises at least one of fused silica, fumed silica, titanium dioxide (TiO_2), or metal particles in the binder. In certain embodiments, the first light-altering material is arranged around an entire perimeter of the first LED chip and around an entire perimeter of the second LED chip. The LED device may further comprise: a first wavelength conversion element registered with the first LED chip, wherein the first wavelength conversion element comprises a first superstrate and a first lumiphoric material that is arranged between the first superstrate and the first LED chip; and a second wavelength conversion element registered with the second LED chip, wherein the second wavelength conversion element comprises a second superstrate and a second lumiphoric material that is arranged between the second superstrate and the second LED chip. In certain embodiments, the first light-altering material is further arranged between the first wavelength conversion element and the second wavelength conversion element.

In another aspect, and LED device comprises: a submount; a first LED chip and a second LED chip on a surface of the submount, wherein the first LED chip is laterally separated from the second LED chip on the surface; and a first light-altering material arranged between the first LED chip and the second LED chip on the submount, wherein the first light-altering material comprises: a binder comprising a first index of refraction; one or more first particles comprising a second index of refraction; and one or more second particles comprising an third index of refraction; wherein the second index of refraction is at least two times greater than the first index of refraction, and the third index of refraction is at least two and a half times greater than the first index of refraction. In certain embodiments, the second index of refraction is in a range of at least two times greater to about three times greater than the first index of refraction, and the third index of refraction is in a range of at least two and a half times greater to about four times greater than the first index of refraction. The one or more first particles may comprise at least one of fused silica, fumed silica, or titanium dioxide, or combinations thereof. The one or more second particles comprise at least one of nanowires or mesowires, or combinations thereof. In certain embodiments, the one or more second particles may comprise at least one of nanoparticles or mesoparticles. In certain embodiments, the first light-altering material is arranged around an entire perimeter of the first LED chip and around an entire perimeter of the second LED chip. The first light-altering material may further comprise metal particles.

In another aspect, an LED device comprises: a submount; a first LED chip and a second LED chip on a surface of the submount, wherein the first LED chip is laterally separated from the second LED chip on the surface; and a light-altering material arranged between the first LED chip and the second LED chip on the submount, wherein the light-altering material comprises: a binder; one or more first particles configured to substantially refract light emitted from the first LED chip and the second LED chip; and one or more second particles configured to refract light and absorb light emitted from the first LED chip and the second LED chip. In certain embodiments, the one or more first particles comprise at least one of fused silica, fumed silica, or titanium dioxide (TiO_2). In certain embodiments, the one or more second particles comprise at least one of nanowires, mesowires, nanoparticles, mesoparticles, nanopowder, or mesopowder. The light-altering material may further comprise one or more third particles configured to substantially reflect light emitted from the first LED chip and the second LED chip. The one or more third particles may comprise metal particles. In certain embodiments, the one or more first particles comprise a reflectance percentage in a range from about 80% to about 100% for light emitted from the first LED chip and the second LED chip. In certain embodiments, the one or more second particles comprise a reflectance percentage in a range from about 20% to about 70% for light emitted from the first LED chip and the second LED chip. The one or more first particles may comprise a weight percent that is in a range of about 10% to about 90%, in a range from about 25% to about 70% of a total weight of the light-altering material. The one or more second particles may comprise a weight percent that is in a range of about greater than 0% to about 15%, or in a range of about greater than 0% to about 10%, in a range of about greater than 0% to about 5%, or in a range of about greater than 0% to about 1% of a total weight of the light-altering material.

In another aspect, any of the foregoing aspects, and/or various separate aspects and features as described herein, may be combined for additional advantage. Any of the various features and elements as disclosed herein may be combined with one or more other disclosed features and elements unless indicated to the contrary herein.

Those skilled in the art will appreciate the scope of the present disclosure and realize additional aspects thereof after reading the following detailed description of the preferred embodiments in association with the accompanying drawing figures.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

The accompanying drawing figures incorporated in and forming a part of this specification illustrate several aspects of the disclosure, and together with the description serve to explain the principles of the disclosure.

FIG. **1**A is a top view of an LED device with a plurality of LED chips arranged on a submount.

FIG. **1**B is a side cross-sectional view taken along the section line of the LED device of FIG. **1**A.

FIG. **2**A is top view of an LED device with a plurality of LED chips arranged on a submount as previously described.

FIG. **2**B is a line plot of an illumination profile when some of the LED chips of FIG. **2**A are electrically activated, and some of the LED chips of FIG. **2**A are electrically deactivated.

FIG. **3**A is a side cross-sectional view of an LED device with a plurality of LED chips arranged on a submount according to embodiments disclosed herein.

FIG. **3**B is a side cross-sectional view of an LED device with a plurality of LED chips arranged on a submount according to embodiments disclosed herein.

FIG. **3**C is a plot representing contrast measurements for several configurations of the LED device of FIG. **3**A.

FIG. **4** is a plot representing illuminance and contrast ratio measurements of the configurations of FIG. **3**C at various drive currents.

FIG. **5** is a side cross-sectional view of an LED device with a plurality of LED chips arranged on a first surface of a submount according to embodiments disclosed herein.

FIG. **6** is a side cross-sectional view of an LED device with a plurality of LED chips arranged on a first surface of a submount according to embodiments disclosed herein.

FIG. **7** is a side cross-sectional view of an LED device with a plurality of LED chips arranged on a first surface of a submount according to embodiments disclosed herein.

FIG. **8** is a side cross-sectional view of an LED device with a plurality of LED chips arranged on a first surface of a submount according to embodiments disclosed herein.

FIG. **9** is a top view of an LED package including a plurality of LED chips on a first surface of a submount according to embodiments disclosed herein.

FIG. **10**A is a top view of an LED package including a plurality of LED chips on a first surface of a submount according to embodiments disclosed herein.

FIG. **10**B is a bottom view of the LED package of FIG. **10**A.

FIG. **11**A is a top view of a submount configured for an individually controllable LED array according to embodiments disclosed herein.

FIG. **11**B is a bottom view of the submount of FIG. **11**A.

FIG. **12** is top view of an LED device that includes a first submount and a second submount that are positioned adjacent to one another.

FIG. **13**A is a top view of a submount configured for an individually controllable LED array according to embodiments disclosed herein.

FIG. **13**B is a bottom view of the submount of FIG. **13**A.

FIG. **14** is top view of a lighting device that includes a plurality of submounts that are positioned adjacent to one another.

FIG. **15** is a top view of a lighting device that includes the plurality of submounts and the first plurality of LED chips, the second plurality of LED chips, and the third plurality of LED chips of FIG. **14** as well as a light-altering material.

FIG. **16** is a top view of a lighting device, or an LED device, that includes the submount of FIG. **13**A with the plurality of LED chips and the light-altering material of FIG. **15**.

FIG. **17**A is top view of an LED device with one or more LED chips arranged on a surface of a submount.

FIG. **17**B is a line plot of an illumination profile when one of the LED chips of FIG. **17**A is electrically activated, and the other LED chips of FIG. **17**A are electrically deactivated for two samples with different light-altering materials.

FIG. **18** is a comparison plot showing the relationship of varying weight percentages of a silicon nanowire/nanopowder mixture on luminance and contrast ratio.

FIGS. **19**A and **19**B illustrate possible interactions of light within an LED device as disclosed herein.

DETAILED DESCRIPTION

The embodiments set forth below represent the necessary information to enable those skilled in the art to practice the embodiments and illustrate the best mode of practicing the embodiments. Upon reading the following description in light of the accompanying drawing figures, those skilled in the art will understand the concepts of the disclosure and will recognize applications of these concepts not particularly addressed herein. It should be understood that these concepts and applications fall within the scope of the disclosure and the accompanying claims.

It will be understood that, although the terms first, second, etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element could be termed a second element, and, similarly, a second element could be termed a first element, without departing from the scope of the present disclosure. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

It will be understood that when an element such as a layer, region, or substrate is referred to as being "on" or extending "onto" another element, it can be directly on or extend directly onto the other element or intervening elements may also be present. In contrast, when an element is referred to as being "directly on" or extending "directly onto" another element, there are no intervening elements present. Likewise, it will be understood that when an element such as a layer, region, or substrate is referred to as being "over" or extending "over" another element, it can be directly over or extend directly over the other element or intervening elements may also be present. In contrast, when an element is referred to as being "directly over" or extending "directly over" another element, there are no intervening elements present. It will also be understood that when an element is referred to as being "connected" or "coupled" to another element, it can be directly connected or coupled to the other element or intervening elements may be present. In contrast, when an element is referred to as being "directly connected" or "directly coupled" to another element, there are no intervening elements present.

Relative terms such as "below" or "above" or "upper" or "lower" or "horizontal" or "vertical" may be used herein to describe a relationship of one element, layer, or region to another element, layer, or region as illustrated in the Figures. It will be understood that these terms and those discussed above are intended to encompass different orientations of the device in addition to the orientation depicted in the Figures.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the disclosure. As used herein, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises," "comprising," "includes," and/or "including" when used herein specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. It will be further understood that terms used herein should be interpreted as having a meaning that is consistent with their meaning in the context of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

Aspects disclosed herein relate to light-emitting diodes (LEDs), LED arrays, and related devices. An LED device includes a first LED chip and a second LED chip mounted on a submount with a light-altering material between the first LED chip and the second LED chip. The light-altering material may include at least one or more of a light-reflective material and a light-absorbing material. In certain embodiments, the light-altering material may include at least one of nanoparticles, nanowires, mesoparticles, or mesowires. Individual wavelength conversion elements may be arranged on each of the first LED chip and the second LED chip. The light-altering material may improve contrast between the first LED chip and the second LED chip as well as between the individual wavelength conversion elements. LED devices may include submounts with at least one electrically conductive anode or cathode path that is discontinuous on a surface of the submount where LED chips are mounted. LED devices may include submounts in modular configurations where LED chips may be mounted on adjacent submounts to form an LED array. Each LED chip of the LED array may be laterally separated from at least one other LED chip by a same distance, and a light-altering material may be arranged around the LED array.

An LED chip typically comprises an active LED structure or region that can have many different semiconductor layers arranged in different ways. The fabrication and operation of LEDs and their active structures are generally known in the art and are only briefly discussed herein. The semiconductor layers of the active LED structure can be fabricated using known processes with a suitable process being fabrication using metal organic chemical vapor deposition. The semiconductor layers of the active LED structure can comprise many different layers and generally comprise an active layer sandwiched between n-type and p-type oppositely doped epitaxial layers, all of which are formed successively on a growth substrate. It is understood that additional layers and elements can also be included in the active LED structure, including but not limited to: buffer layers, nucleation layers, super lattice structures, un-doped layers, cladding layers, contact layers, current-spreading layers, and light extraction layers and elements. The active layer can comprise a single quantum well, a multiple quantum well, a double heterostructure, or super lattice structures.

The active LED structure can be fabricated from different material systems, with some material systems being Group III nitride-based material systems. Group III nitrides refer to those semiconductor compounds formed between nitrogen and the elements in Group III of the periodic table, usually aluminum (Al), gallium (Ga), and indium (In). Gallium nitride (GaN) is a common binary compound. Group III nitrides also refer to ternary and quaternary compounds such as aluminum gallium nitride (AlGaN), indium gallium nitride (InGaN), and aluminum indium gallium nitride (AlInGaN). For Group III nitrides, silicon (Si) is a common n-type dopant and magnesium (Mg) is a common p-type dopant. Accordingly, the active layer, n-type layer, and p-type layer may include one or more layers of GaN, AlGaN, InGaN, and AlInGaN that are either undoped or doped with Si or Mg for a material system based on Group III nitrides. Other material systems include silicon carbide (SiC), organic semiconductor materials, and other Group III-V systems such as gallium phosphide (GaP), gallium arsenide (GaAs), and related compounds.

The active LED structure may be grown on a growth substrate that can include many materials, such as sapphire, SiC, aluminum nitride (AlN), GaN, with a suitable substrate being a 4H polytype of SiC, although other SiC polytypes can also be used including 3C, 6H, and 15R polytypes. SiC has certain advantages, such as a closer crystal lattice match to Group III nitrides than other substrates and results in Group III nitride films of high quality. SiC also has a very high thermal conductivity so that the total output power of Group III nitride devices on SiC is not limited by the thermal dissipation of the substrate. Sapphire is another common substrate for Group III nitrides and also has certain advantages including being lower cost, having established manufacturing processes, and having good light transmissive optical properties.

Different embodiments of the active LED structure can emit different wavelengths of light depending on the composition of the active layer and n-type and p-type layers. In certain embodiments, the active LED structure emits a blue light in a peak wavelength range of approximately 430 nanometers (nm) to 480 nm. In other embodiments, the active LED structure emits green light in a peak wavelength range of 500 nm to 570 nm. In other embodiments, the active LED structure emits red light in a peak wavelength range of 600 nm to 650 nm. The LED chip can also be covered with one or more lumiphors or other conversion materials, such as phosphors, such that at least some of the light from the LED chip passes through the one or more phosphors and is converted to one or more different wavelengths of light. In certain embodiments, the LED chip emits a generally white light combination of light from the active LED structure and light from the one or more phosphors. The one or more phosphors may include yellow (e.g., YAG:Ce), green (LuAg:Ce), and red ($Ca_{i-x-y}Sr_xEu_yAlSiN_3$) emitting phosphors, and combinations thereof.

In certain embodiments, a wavelength conversion element includes one or more lumiphors or a lumiphoric material that is disposed on a superstrate. The term "superstrate" as used herein refers to an element placed on an LED chip with a lumiphoric material between the superstrate and the LED chip. The term "superstrate" is used herein, in part, to avoid confusion with other substrates that may be part of the semiconductor light emitting device, such as a growth or carrier substrate of the LED chip or a submount of an LED package. The term "superstrate" is not intended to limit the orientation, location, and/or composition of the structure it describes. In certain embodiments, the superstrate may be composed of, for example, sapphire, SiC, silicone, and/or glass (e.g., borosilicate and/or fused quartz). The superstrate may be patterned to enhance light extraction from the LED chip as described in commonly-assigned U.S. Provisional Application No. 62/661,359 entitled "Semiconductor Light Emitting Devices Including Superstrates With Patterned Surfaces" which is hereby incorporated by reference herein. The superstrate may also be configured as described in commonly-assigned U.S. Patent Application Publication No. 2018/0033924, also incorporated by reference herein. The superstrate may be formed from a bulk substrate which is optionally patterned and then singulated. In certain embodiments, the patterning of the superstrate may be performed by an etching process (e.g., wet or dry etching). In certain embodiments, the patterning of the superstrate may be performed by otherwise altering the surface, such as by a laser or saw. In certain embodiments, the superstrate may be thinned before or after the patterning process is performed. The lumiphoric material may then be placed on the superstrate by, for example, spraying and/or otherwise coating the superstrate with the lumiphoric material. The superstrate and the lumiphoric material may be attached to the LED chip using, for example, a layer of transparent adhesive. In certain embodiments, when the superstrate is attached to the LED chip, a portion of the transparent adhesive is positioned at least partially between lateral edges of the LED chip. In certain embodiments, a single wavelength conversion element may cover multiple LED chips. In other embodiments, individual wavelength conversion elements may be registered with individual LED chips.

The present disclosure can include LED chips having a variety of geometries, such as vertical geometry or lateral geometry. A vertical geometry LED chip typically includes an anode and cathode on opposing sides of the active LED structure. A lateral geometry LED chip typically includes an anode and a cathode on the same side of the active LED structure that is opposite a substrate, such as a growth substrate or a carrier substrate. In certain embodiments, a lateral geometry LED chip may be mounted on a submount of an LED package such that the anode and cathode are on a face of the active LED structure that is opposite the submount. In this configuration, wire bonds may be used to provide electrical connections with the anode and cathode. In other embodiments, a lateral geometry LED chip may be flip-chip mounted on a submount of an LED package such that the anode and cathode are on a face of the active LED structure that is adjacent to the submount. In this configuration, electrical traces or patterns may be provided on the submount for providing electrical connections to the anode and cathode of the LED chip. In a flip-chip configuration, the active LED structure is configured between the substrate of the LED chip and the submount for the LED package. Accordingly, light emitted from the active LED structure may pass through the substrate in a desired emission direction. In certain embodiments, the flip-chip LED chip may be configured as described in commonly-assigned U.S. Patent Application Publication No. 2017/0098746, which is hereby incorporated by reference herein.

Embodiments of the disclosure are described herein with reference to cross-sectional view illustrations that are schematic illustrations of embodiments of the disclosure. As such, the actual thickness of the layers can be different, and variations from the shapes of the illustrations as a result, for example, of manufacturing techniques and/or tolerances, are expected. For example, a region illustrated or described as square or rectangular can have rounded or curved features, and regions shown as straight lines may have some irregularity. Thus, the regions illustrated in the figures are schematic and their shapes are not intended to illustrate the precise shape of a region of a device and are not intended to limit the scope of the disclosure.

FIG. **1**A is a top view of an LED device **10** with a plurality of LED chips **12-1** to **12-6** arranged on a submount **14**. While the LED device **10** is illustrated with six LED chips **12-1** to **12-6**, any number of LED chips are possible. In certain embodiments, LED devices according to embodiments disclosed herein may include an array of LED chips with as few as two LED chips or as many as one hundred LED chips or more. The submount **14** can be formed of many different materials with an exemplary material being electrically insulating. Suitable materials include, but are not limited to ceramic materials such as aluminum oxide or alumina, AlN, or organic insulators like polyimide (PI) and polyphthalamide (PPA). In other embodiments, the submount **14** can comprise a printed circuit board (PCB), sapphire, Si or any other suitable material. For PCB embodiments, different PCB types can be used such as a standard FR-4 PCB, a metal core PCB, or any other type of PCB. FIG. **1**B is a side cross-sectional view taken along the section line of the LED device **10** of FIG. **1**A. As illustrated, the LED chip **12-1** and the LED chip **12-2** are laterally separated on a first surface **16** of the submount **14**. A first wavelength conversion element **18-1** is registered with the first LED chip **12-1**, and a second wavelength conversion element **18-2** is registered with the second LED chip **12-2**. The first wavelength conversion element **18-1** may include a first lumiphoric material **20-1** and a first superstrate **22-1**, and the second wavelength conversion element **18-2** may include a second lumiphoric material **20-2** and a second superstrate **22-2**. In certain embodiments, the first lumiphoric material **20-1** and the second lumiphoric material **20-2** are respectively disposed on the first superstrate **22-1** and the second superstrate **22-2**. Notably, in this configuration, the lumiphoric materials **20-1**, **20-2** are not located in the space between the LED chips **12-1**, **12-2** on the submount **14**, thereby reducing light conversion and improving contrast between the LED chips **12-1**, **12-2**. Light emitted from an active region of an LED structure or light that is converted by a lumiphoric material is typically omnidirectional in nature. Accordingly, a portion of light emitted from either the first LED chip **12-1** or converted by the first lumiphoric material **20-1** may travel laterally toward the second LED chip **12-2**. In this regard, some light from the first LED chip **12-1** may bleed over to the relative position of the second LED chip **12-2** and decrease contrast between the two LED chips **12-1**, **12-2**. Additionally, at least some of the lateral light from one of the LED chips **12-1**, **12-2** may be lost to absorption within the other of the LED chips **12-1**, **12-2**. In some applications, it may be desirable for a combined emission area between the two LED chips **12-1**, **12-2** to appear as a uniform emission area. However, in other applications, such as those where each of the LED chips **12-1**, **12-2** can be electrically activated (turned on) or electrically de-activated (turned off) independently of each other, the contrast between the LED chips **12-1**, **12-2** may be lower than what is desired.

FIG. **2**A is top view of an LED device **24** with a plurality of LED chips **26-1** to **26-6** arranged on a submount **28** as previously described. FIG. **2**B is a line plot of an illumination profile when the LED chips **26-2**, **26-4**, and **26-5** are electrically activated, and the LED chips **26-1**, **26-3**, and **26-6** are electrically deactivated. The y-axis of the plot is luminance in candela per square centimeter (cd/cm^2) and the x-axis is the relative distance in millimeters (mm) a sensor moves across the plurality of LED chips **26-1** to **26-6** in a direction as indicated by the dashed line **29** of FIG. **2**A. In the plot of FIG. **2**B, a first high luminance area **30** indicates the relative position of the LED chip **26-2**, and a second broader high luminance area **32** indicates the relative position of the LED chips **26-4**, **26-5**. A luminance valley **34** is located between the high luminance areas **30** and **32** and indicates the relative position of the LED chip **26-3**. As shown in the plot, even though the LED chip **26-3** is electrically deactivated, an elevated luminance is measured due to lateral emissions and cross-talk from the LED chips **26-2**, **26-4**, and **26-5**. In this regard, contrast between the electrically activated LED chips **26-2**, **26-4**, **26-5** and the electrically de-activated LED chips **26-1**, **26-3**, and **26-6** is lower that what is desired for certain applications.

In certain embodiments, a light-emitting device includes at least two LED chips that are laterally separated on a submount. A separate wavelength conversion element may be registered with each LED chip. To improve contrast between adjacent LED chips, a light-altering material may be arranged between the adjacent LED chips. The light-altering material may be adapted for dispensing, or placing, and may include many different materials including light-reflective materials that reflect or redirect light, light-absorbing materials that absorb light, and materials that act as a thixotropic agent. As used herein, the term “light-reflective” refers to materials or particles that reflect, refract, or otherwise redirect light. For light-reflective materials, the light-altering material may include at least one of fused silica, fumed silica, titanium dioxide (TiO$_2$), or metal particles suspended in a binder, such as silicone or epoxy. Particles of TiO_2 are generally more light-refracting while metal particles are generally more light-reflecting. In certain embodiments, metal particles may include Al particles, silver (Ag) particles, or combinations thereof. Al and Ag particles may have a nominal particle size of about 500 nm, or in a range including about 300 nm. The metal particles may comprise spherical powder, although other shapes including irregular shapes are possible. In certain embodiments, the light-reflecting materials comprise a generally white color. For light-absorbing materials, the light-altering material may include at least one of carbon, silicon, or metal particles suspended in a binder, such as silicon or epoxy. In certain embodiments, the light-absorbing materials comprise a generally black color. The light-reflective materials and the light-absorbing materials may comprise nanoparticles. In certain embodiments, the light-altering material includes both light-reflective materials and light-absorbing material suspended in a binder. A weight ratio of the light-reflective material to the binder may comprise a range of about 1:1 to about 2:1. A weight ratio of the light-absorbing material to the binder may comprise a range of about 1:400 to about 1:10. In certain embodiments, a total weight of the light-altering material includes any combination of the binder, the light-reflective material, and the light-absorbing material. In some embodiments, the binder may comprise a weight percent that is in a range of about 10% to about 90% of the total weight of the light-altering material; the light-reflective material may comprise a weight percent that is in a range of about 10% to about 90% of the total weight of the light-altering material; and the light-absorbing material may comprise a weight percent that is in a range of about 0% to about 15% of the total weight of the light-altering material. In further embodiments, the light-absorbing material may comprise a weight percent that is in a range of about greater than 0% to about 15% of the total weight of the light-altering material. In further embodiments, the binder may comprise a weight percent that is in a range of about 25% to about 70% of the total weight of the light-altering material; the light-reflective material may comprise a weight percent that is in a range of about 25% to about 70% of the total weight of the light-altering material; and the light-absorbing material may comprise a weight percent that is in a range of about 0% to about 5% of the total weight of the light-altering material. In further embodiments, the light-absorbing material may comprise a weight percent that is in a range of about greater than 0% to about 5% of the total weight of the light-altering material. In certain embodiments, the light-altering material may comprise a generally white color to reflect and redirect light. In other embodiments, the light-altering material may comprise a generally opaque or black color for absorbing light and increasing contrast of an LED package. The light-altering material can be dispensed or deposited in place using an automated dispensing machine where any suitable size and/or shape can be formed. The light-altering material may have a viscosity configured to be dispensed around a perimeter of an LED chip and surface tension will keep the light-altering material off of a primary emitting surface of the LED chip. Additionally, the light-altering material may wick in between adjacent LED chips that are separated by narrow lateral distances.

FIG. **3**A is a side cross-sectional view of an LED device **36** with a plurality of LED chips **38-1** to **38-2** arranged on a submount **40** according to embodiments disclosed herein. A first wavelength conversion element **42-1** that includes a first lumiphoric material **44-1** and a first superstrate **46-1** is registered with the first LED chip **38-1**. A second wavelength conversion element **42-2** that includes a second lumiphoric material **44-2** and a second superstrate **46-2** is registered with the second LED chip **38-2**. A light-altering material **48** is arranged between the first LED chip **38-1** and the second LED chip **38-2** on the submount **40**. In certain embodiments, the light-altering material **48** extends from a first surface **49** of the submount **40** to a height that is at least level with the LED chips **38-1**, **38-2**. In further embodiments, the light-altering material **48** extends from the first surface **49** to a height that is at least level with the lumiphoric materials **44-1**, **44-2**. In still further embodiments, the light-altering material **48** extends from the first surface **49** to a height that is at least level with the wavelength conversion elements **42-1**, **42-2**. In certain embodiments, the light-altering material **48** includes light-reflective particles and light-absorbing particles that are interspersed and suspended in a same binder.

FIG. **3**B is a side cross-sectional view of an additional embodiment of the LED device **36** of FIG. **3**A. As previously described, the plurality of LED chips **38-1** to **38-2** are arranged on the submount **40**, the first wavelength conversion element **42-1** that includes the first lumiphoric material **44-1** and the first superstrate **46-1** is registered with the first LED chip **38-1**, and the second wavelength conversion element **42-2** that includes the second lumiphoric material **44-2** and the second superstrate **46-2** is registered with the second LED chip **38-2**. In FIG. **3**B, a first light-altering material **48**A and a second light-altering material **48**B are arranged between the first LED chip **38-1** and the second LED chip **38-2** on the submount **40**. In certain embodiments, a combination of the first and second light-altering materials **48**A, **48**B extends from the first surface **49** of the submount **40** to a height that is at least level with the LED chips **38-1**, **38-2**. In further embodiments, the combination of the first and second light-altering materials **48**A, **48**B extends from the first surface **49** to a height that is at least level with the lumiphoric materials **44-1**, **44-2**. In still further embodiments, the combination of the first and second light-altering materials **48**A, **48**B extends from the first surface **49** to a height that is at least level with the wavelength conversion elements **42-1**, **42-2**. The first and second light-altering materials **48**A, **48**B may be formed separately from one another by sequential dispensing or other deposition steps.

In certain embodiments, the first and second light-altering materials **48**A, **48**B includes light-reflective particles and light-absorbing particles that are interspersed and suspended in a same binder. In certain embodiments, the first light-altering material **48**A comprises a different amount of light-reflective particles and/or light-absorbing particles than the second light-altering material **48**B. For example, the first light-altering material **48**A may comprise a lower amount of light-absorbing particles than the second light-altering material **48**B. In certain embodiments, the first light-altering material **48**A comprises no light-absorbing materials. In certain embodiments, the second light-altering material **48**B may comprise at least two times the amount of light-absorbing particles as the first light-altering material **48**A. In further embodiments, the second light-altering material **48**B may comprise at least five times, or in a range of five times to ten times or more the amount of light-absorbing particles as the first light-altering material **48**A. In this regard, the first light-altering material **48**A is configured to reflect more light between the first LED chip **38-1** and the second LED chip **38-2** while the second light-altering material **48**B is configured to provide more contrast between the first wavelength conversion element **42-1** and the second wavelength conversion element **42-2**. Depending on the application, the order may be reversed in other embodiments such that the second light-altering material **48**B comprises a lower amount of light-absorbing particles than the first light-altering material **48**A. The amounts may differ in a similar manner as previously described. In this regard, the first light-altering material **48**A may provide higher contrast between the first LED chip **38-1** and the second LED chip **38-2** while the second light-altering material **48**B provides higher reflectivity between the first wavelength conversion element **42-1** and the second wavelength conversion element **42-2**. In other embodiments, only one of the first light-altering material **48**A and the second light altering material **48**B comprises light-reflective and/or light absorbing particles while the other is substantially clear.

FIG. **3**C is a plot representing contrast measurements for several configurations of the LED device **36** of FIG. **3**A. In a first configuration, labeled "Sample 1" in FIG. **3**C, the light-altering material **48** of FIG. **3**A includes a weight ratio of TiO_2 (light-reflective particles) to a silicone binder of about 1:1. In a second configuration, labeled "Sample 2" in FIG. **3**C, the light-altering material **48** of FIG. **3**A includes the same composition as Sample 1 with an addition of carbon particles (light-absorbing particles) in a weight ratio of about 1:25 of the binder. In a third configuration, labeled "Sample 3" in FIG. **3**C, the light-altering material **48** of FIG. **3**A includes the same composition as Sample 1 with an addition of carbon particles (light-absorbing particles) in a weight ratio of about 1:12.5 of the binder. For each of the Samples 1, 2, and 3, the light-reflective particles and the light-absorbing particles (only Samples 2 and 3) are interspersed and suspended in the same binder of silicone. The y-axis in FIG. **3**C represents arbitrary units of a contrast ratio as defined by a ratio of luminance between an electrically activated LED chip (on) and an adjacent LED chip that is electrically deactivated (off). A higher contrast ratio indicates a higher delta between the measured luminance of the electrically activated LED chip compared to the electrically deactivated LED chip. The x-axis represents various configurations for the LED chip (or die) spacing for each of the samples in microns (μm). As shown by the plot, the configurations of Sample 2 and Sample 3 demonstrated notably higher contrast ratios for all LED chip spacings.

The addition of light-absorbing particles between LED chips can lead to a nominal decrease in brightness. However, this can be compensated for by increasing a drive current to the LED chips. FIG. **4** is a plot representing illuminance and contrast ratio measurements of the Samples 1, 2, and 3 of FIG. **3**C at various drive currents. The x-axis represents the die spacing (in μm) and drive current (in amps) for each of the samples. The y-axis represents both illuminance in candela per square millimeter (cd/mm^2) and the contrast ratio. As expected, the illuminance values are lower for the Samples 2 and 3 that include light-absorbing particles. However, the drive current for the Samples 2 and 3 may be increased to increase the illuminance values and the contrast ratios remain notable higher than Sample 1 that does not include light-absorbing particles.

In certain embodiments, different configurations of light-reflective materials and light-absorbing materials may be provided. For example, a light-altering material that includes a first light-reflective material may be provided between two LED chips and a gap may be formed that extends through the light-altering material to a submount on which the LED chips are mounted. In certain embodiments, a second light-reflective material may be provided in the gap. In certain embodiments, a light-absorbing material may be provided in the gap. In still further embodiments, both of the second light-reflective material and the light-absorbing material may be provided in the gap. In this manner, further improvements to the illuminance and contrast ratio of adjacent LED chips may be realized.

FIG. **5** is a side cross-sectional view of an LED device **50** with a plurality of LED chips **52-1** to **52-2** arranged on a first surface **54** of a submount **56** according to embodiments disclosed herein. The LED device **50** additionally includes: a first wavelength conversion element **58-1** with a first lumiphoric material **60-1** and a first superstrate **62-1**; a second wavelength conversion element **58-2** with a second lumiphoric material **60-2** and a second superstrate **62-2**; and a light-altering material **64** as previously described. In FIG. **5**, a portion of the light-altering material **64** is removed or never deposited to form a gap **66** in the light-altering material **64** between a first LED chip **52-1** and a second LED chip **52-2**. In certain embodiments, the gap **66** extends through the light-altering material **64** to the first surface **54** of the submount **56**. The gap **66** may provide an index of refraction delta with the light-altering material **64**. In this manner, light traveling laterally between the LED chips **52-1**, **52-2** and the wavelength conversion elements **58-1**, **58-2** may be redirected in a desired direction, thereby improving overall illuminance levels and contrast between the LED chips **52-1**, **52-2**.

FIG. **6** is a side cross-sectional view of an LED device **68** with a plurality of LED chips **70-1** to **70-2** arranged on a first surface **72** of a submount **74** according to embodiments disclosed herein. The LED device **68** additionally includes: a first wavelength conversion element **76-1** with a first lumiphoric material **78-1** and a first superstrate **80-1**; a second wavelength conversion element **76-2** with a second lumiphoric material **78-2** and a second superstrate **80-2**; a first light-altering material **82**; and a gap **84** as previously described. In FIG. **6**, a second light-altering material **86** is formed on the first light-altering material **82**. The second light-altering material **86** may be formed by selective thin film deposition, such as through a mask, in the gap **84**. The second light-altering material **86** may include at least one of a light-reflective-material and/or a light-absorbing material as previously described. In certain embodiments, the second light-altering material **86** comprises a layer of reflective metal and the first light-altering material **82** comprises light-reflective particles. In other embodiments, the second light-altering material **86** comprises light-absorbing particles and the first light-altering material **82** comprises light-reflective particles. In other embodiments, the second light-altering material **86** comprises light-reflective particles and the first light-altering material **82** comprises light-absorbing particles. In still further embodiments, the first light-altering material **82** and the second light-altering material **84** may both include light-reflective particles and light-absorbing particles in differing amounts.

FIG. **7** is a side cross-sectional view of an LED device **88** with a plurality of LED chips **90-1** to **90-2** arranged on a first surface **92** of a submount **94** according to embodiments disclosed herein. The LED device **88** additionally includes: a first wavelength conversion element **96-1** with a first lumiphoric material **98-1** and a first superstrate **100-1**; a second wavelength conversion element **96-2** with a second lumiphoric material **98-2** and a second superstrate **100-2**; and a first light-altering material **102** as previously described. In FIG. **7**, a second light-altering material **104** fills a gap (**66** of FIG. **5**) formed in the first light-altering material **102**. The second light-altering material **104** may be formed by dispensing or depositing in the gap (**66** of FIG. **5**). The second light-altering material **104** may include at least one of a light-reflective-material and/or a light-absorbing material as previously described. In certain embodiments, the second light-altering material **104** comprises light-absorbing particles and the first light-altering material **102** comprises light-reflective particles. In other embodiments, the second light-altering material **104** comprises light-reflective particles and the first light-altering material **102** comprises light-absorbing particles. In still further embodiments, the first light-altering material **102** and the second light-altering material **104** may both include light-reflective particles and light-absorbing particles in differing amounts. In certain embodiments, the second light-altering material **104** extends above the first light-altering material **102** in a direction away from the first surface **92** of the submount **94**. In this regard, more light traveling laterally may be redirected or absorbed between the LED chips **90-1**, **90-2**, thereby further improving contrast.

FIG. **8** is a side cross-sectional view of an LED device **106** with a plurality of LED chips **108-1** to **108-2** arranged on a first surface **110** of a submount **112** according to embodiments disclosed herein. The LED device **106** additionally includes: a first wavelength conversion element **114-1** with a first lumiphoric material **116-1** and a first superstrate **118-1**; a second wavelength conversion element **114-2** with a second lumiphoric material **116-2** and a second superstrate **118-2**; and a first light-altering material **120** as previously described. In FIG. **8**, a second light-altering material **122** and a third light-altering material **124** fills a gap (**66** of FIG. **5**) formed in the first light-altering material **120**. The second light-altering material **122** is similar to the second light-altering material **86** of FIG. **5**, and the third light-altering material **124** is similar to the second light-altering material **104** of FIG. **7**. In certain embodiments, the first light-altering material **120** includes light-reflective particles, the second light-altering material **122** includes a layer of reflective metal, and the third light-altering material **124** includes light-absorbing particles. In other embodiments, the first light-altering material **120** includes light-absorbing particles and the third light-altering material **124** includes light-reflective particles. In still other embodiments, the first light-altering material **120**, the second light-altering material **122**, and the third light-altering material **124** may all include both light-reflective particles and light-absorbing particles, but in differing amounts.

Embodiments as disclosed herein may be particularly suited for LED devices or packages that include a plurality of LED chips that form an LED array on a submount. Anode and cathode bond pads may be provided on the submount that are configured to receive an external electrical connection, such as wirebonds. Electrically conductive anode paths and electrically conductive cathode paths are configured to electrically connect the anode and cathode bond pads with the plurality of LED chips. In certain embodiments, the anode and cathode bond pads are on a same surface of the submount on which the plurality of LED chips are mounted. In other embodiments, the anode and cathode bond pads are on an opposite surface of the submount from the plurality of LED chips.

FIG. **9** is a top view of an LED package **126** including a plurality of LED chips **128-1** to **128-3** on a first surface **130**, or face, of a submount **132** according to embodiments disclosed herein. A first bond pad **134-1** and a second bond pad **134-2** are provided on the first surface **130** of the submount **132** and laterally spaced away from the plurality of LED chips **128-1** to **128-3** on the first surface **130**. Depending on the configuration, the first bond pad **134-1** may comprise either a cathode bond pad or an anode bond pad and the second bond pad **134-2** may comprise the other of the cathode bond pad or the anode bond pad. A light-altering material **136** as previously described is arranged around an entire perimeter of a first LED chip **128-1**, around an entire perimeter of a second LED chip **128-2**, and around an entire perimeter of a third LED chip **128-3**. In certain embodiments, individual wavelength conversion elements **138-1** to **138-3** are separately registered with each of the plurality of LED chips **128-1** to **128-3**. The light-altering material **136** is additionally arranged around an entire perimeter of each of the wavelength conversion elements **138-1** to **138-3**. In certain embodiments, at least a portion of the light-altering material **136** extends to a lateral edge of the first surface **130** of the submount **132**. In FIG. **9**, the light-altering material **136** extends to three of the four lateral edges of the submount **132**. In this manner, the light-altering material **136** does not extend to the fourth lateral edge of the submount **132** that is adjacent the first bond pad **134-1** and the second bond pad **134-2**. Accordingly, the first bond pad **134-1** and the second bond pad **134-2** are uncovered by the light-altering material **136**. In certain embodiments, the light-altering material **136** is configured to redirect or reflect laterally-emitting light from the LED chips **128-1** to **128-3** or the wavelength conversion elements **138-1** to **138-3** toward a desired emission direction. In certain embodiments, the light-altering material **136** may block or absorb at least a portion of any laterally-emitting light from the LED chips **128-1** to **128-3** or the wavelength conversion elements **138-1** to **138-3**. The light-altering material **136** may partially cover the submount **132** outside of where the LED chips **128-1** to **128-3** are located. In this regard, the light-altering material **136** may cover portions of the submount that extend from the first bond pad **134-1** and the second bond pad **134-2** to the LED chips **128-1** to **128-3**, while leaving the first bond pad **134-1** and the second bond pad **134-2** uncovered. A first electrically conductive path **140-1** electrically connects the first bond pad **134-1** to at least one of the plurality of LED chips **128-1** to **128-3** and a second electrically conductive path **140-2** electrically connects the second bond pad **134-2** to at least one of the plurality of LED chips **128-1** to **128-3**. In FIG. **9**, the electrically conductive paths **140-1**, **140-2** are on the first surface **130** of the submount **132** and barely visible outside of the light-altering material **136**. In this regard, the electrically conductive paths **140-1**, **140-2** comprise traces that extend on the first surface **130** under the light-altering material **136**. In other embodiments, the light-altering material **136** entirely covers the electrically conductive paths **140-1**, **140-2**.

FIG. **10**A is a top view of an LED package **142** including a plurality of LED chips **144-1** to **144-3** on a first surface **146** of a submount **148** according to embodiments disclosed herein. The LED package **142** may further include a light-altering material **150** and a plurality of wavelength conversion elements **152-1** to **152-3** as previously described. In FIG. **10**A, the light-altering material **150** covers substantially all of the first surface **146** of the submount **148**. In certain embodiments, at least a portion of the light-altering material **150** extends to all lateral edges of the first surface **146** of the submount **148**. FIG. **10**B is a bottom view of the LED package **142** of FIG. **10**A. A second surface **154** of the submount **148** that opposes the first surface **146** of FIG. **10**A is visible. A first bond pad **156-1** and a second bond pad **156-2** as previously described are arranged on the second surface **154** of the submount **148**. In this manner, the LED package **142** may be configured to be surface mounted to a board (not shown) such that the bond pads **156-1**, **156-2** align with electrical traces or pads on the board. As with the

LED device **126** of FIG. **9**, a first electrically conductive path **158-1** electrically connects the first bond pad **156-1** to at least one of the plurality of LED chips **152-1** to **152-3** (FIG. **10**A), and a second electrically conductive path **158-2** electrically connects the second bond pad **156-2** to at least one of the plurality of LED chips **152-1** to **152-3** (FIG. **10**A). However, in FIG. **10**B, the electrically conductive paths **158-1**, **158-2** extend from the second surface **154** of the submount **148** to the first surface **146**. In that regard, the electrically conductive paths **158-1**, **158-2** may comprise electrically conductive vias that extend through the submount **148**.

As previously described, embodiments as disclosed herein may be particularly suited for LED devices or packages that include a plurality of LED chips that form an LED array on a submount. In certain embodiments, the LED chips of the LED array are individually controllable in a manner such that each of the LED chips may be independently turned on and off. Improved contrast ratios between on and off LED chips in the LED array may be desirable in applications where emission directions and patterns from a LED device are adjustable. Such applications include automotive lighting such as adaptable light sources for headlights, aerospace lighting, general illumination, video screen displays, and pixelated LED arrays. In order to provide an LED device with a plurality of independently controllable LED chips, a submount may include multiple anode and cathode bond pads with multiple electrically conductive anode and cathode paths. In certain embodiments, at least one of the electrically conductive anode and cathode paths is discontinuous along a first face of a submount where the LED chips are mounted. In this regard, a portion of the electrically conductive anode and cathode paths may extend along a second face of the submount that is opposite the first face. Embodiments as disclosed herein may describe particular configurations of anodes and cathodes, anode and cathode bond pads, and electrically conductive anode and cathode paths. It is understood that in other configurations the polarities may be reversed by renaming elements described with anode configurations as cathodes and vice versa.

FIG. **11**A is a top view of a submount **160** configured for an individually controllable LED array according to embodiments disclosed herein. FIG. **11**B is a bottom view of the submount **160** of FIG. **11**A. The submount **160** comprises a first face **162** and a second face **164** that opposes the first face **162**. A plurality of LED chip mounting regions **166-1** to **166-3** are on the first face as indicated by the dashed lines in FIG. **11**A. For illustrative purposes, the location of the plurality of LED chip mounting regions **166-1** to **166-3** relative to the second face **164** are shown in dashed lines in FIG. **11**B. For simplicity, only the LED chip mounting regions **166-1** to **166-3** are labeled. However, the submount **160** as illustrated is configured with LED chip mounting regions for thirty-six individual LED chips and the following description may be applicable to all of the LED chip mounting regions. Additionally, embodiments as disclosed herein are applicable to any number of LED chip mounting regions. A first LED chip mounting region **166-1** includes a first anode **168-1** and a first cathode **170-1**; a second LED chip mounting region **166-2** includes a second anode **168-2** and a second cathode **170-2**; a third LED chip mounting region **166-3** includes a third anode **168-3** and a third cathode **170-3**; and so on. By way of an example, the first anode **168-1** and the first cathode **170-1** are configured to electrically contact a corresponding anode and cathode of an LED chip (not shown) that may be mounted in the first mounting region **166-1**. A plurality of first anode bond pads **172-1** to **172-3** and a plurality of first cathode bond pads **174-1** to **174-3** are arranged on the first face **162** of the submount **160**. For simplicity in FIG. **11**A, only the first anode bond pads **172-1** to **172-3** and the first cathode bond pads **174-1** to **174-3** are labeled. In order to individually control each of the LED chips that will be mounted in the plurality of LED chip mounting regions **166-1** to **166-3**, each LED chip mounting region **166-1** to **166-3** is electrically connected with a unique pair of one of the first anode bond pads **172-1** to **172-3** and one of the first cathode bond pads **174-1** to **174-3**. A plurality of electrically conductive anode paths **176-1** to **176-3** and a plurality of electrically conductive cathode paths **178-1** to **178-3** are used to make these connections. For example, the electrically conductive anode path **176-1** extends between and is continuous with the first anode **168-1** and the first anode bond pad **172-1**; and the electrically conductive cathode path **178-2** (FIG. **11**B) extends between and is continuous with the first cathode **170-1** and the second cathode bond pad **174-2**. In this manner, electrical connections with the first anode bond pad **172-1** and the second cathode bond pad **174-2** may be used to electrically control an LED chip mounted to the first LED chip mounting region **166-1**. In a similar manner, electrical connections with the first anode bond pad **172-1** and the first cathode bond pad **174-1** may be used to electrically control an LED chip mounted to the third LED chip mounting region **166-3**. Accordingly, the third LED chip mounting region **166-3** shares the electrically conductive anode path **176-1** and the first anode bond pad **172-1** with the first LED chip mounting region **166-1**. However, the third LED chip mounting region **166-3** is electrically connected with the first cathode bond pad **174-1** by way of the electrically conductive cathode path **178-1**.

As illustrated in FIGS. **11**A and **11**B, the plurality of electrically conductive cathode paths **178-1** to **178-3** are discontinuous on the first face **162** of the submount **160**. In this manner, the plurality of electrically conductive cathode paths **178-1** to **178-3** extend through the submount **160** to the second face **164** of the submount, and at least a portion of the plurality of electrically conductive cathode paths **178-1** to **178-3** extend on the second face **164**. By way of example, the electrically conductive cathode path **178-1** includes a first electrically conductive via **180-1** that extends from the first cathode bond pad **174-1** on the first face **162** to a second cathode bond pad **182-1** on the second face **164**. A portion of the electrically conductive cathode path **178-1** extends along the second face **164** to an area below the third LED chip mounting region **166-3**. The electrically conductive cathode path **178-1** further includes a second via **180-2** that extends to the third cathode **170-3** on the first face **162**. In this manner, each one of the plurality of first anode bond pads **172-1** to **172-3** is electrically connected to a corresponding one of a plurality of second anode bond pads **184-1** to **184-3** through the submount **160** by vias, and each one of the plurality of first cathode bond pads **174-1** to **174-3** has a corresponding one of the plurality of second cathode bond pad **182-1** to **182-3** that are also electrically connected through the submount **160** by vias. Accordingly, the submount **160** is configured to receive external electrical connections on either of the first face **162** (e.g. by wire bonds) or the second face **164** (e.g. by corresponding electrical traces on a board).

As illustrated in FIGS. **11**A and **11**B, each of the plurality of electrically conductive anode paths **176-1** to **176-3** and each of the plurality of electrically conductive cathode paths **178-1** to **178-3** are configured to be electrically connected with more than one of the plurality of LED chip mounting regions **166-1** to **166-3**. However, in certain embodiments, each LED chip mounting region **166-1** to **166-3** comprises a unique combination of a particular electrically conductive anode path **176-1** to **176-3** and a particular electrically conductive cathode path **178-1** to **178-3**. By sharing electrically conductive anode or cathode paths to control different LED chips, a total number of electrically conductive anode or cathode paths may be reduced while still maintaining independent control of each LED chip that is mounted on the submount **160**. In certain embodiments, the total number of electrically conductive anode and cathode paths may be less than a total number of LED chips. For example, FIGS. **11**A and **11**B illustrate a submount configured with thirty-six different LED chip mounting areas that are configured to receive and independently control thirty-six LED chips with only twelve electrically conductive anode paths and only twelve electrically conductive cathode paths. By having a reduced number of electrically conductive anode or cathode paths, electrical connections on the submount may be simplified. Accordingly, the first surface **162** of the submount **160** may have space for an area **186** that includes identification or other information, including a quick response (QR) code, a bar code, or alphanumeric information.

In certain embodiments, the portions of the electrically conductive cathode paths **178-1** to **178-3** on the second face **164** include expanded dimensions. In this manner, an increased surface area of the second face **164** is covered by the electrically conductive cathode paths **178-1** to **178-3**. In certain embodiments, the electrically conductive cathode paths **178-1** to **178-3** include one or more layers of metal or metal alloys that comprise good thermal conductivity. In this regard, the portions of the electrically conductive cathode paths **178-1** to **178-3** on the second face **164** may additionally serve as heat sinks or heat spreaders to assist with heat dissipation away from LED chips mounted on the first face **162**. In certain embodiments, between about 60% and 95% of the total surface area of the second face **164** is covered by the electrically conductive cathode paths **178-1** to **178-3**. In further embodiments, between about 70% and 80% of the total surface area of the second face **164** is covered by the electrically conductive cathode paths **178-1** to **178-3**. In still further embodiments, between about 70% and 75% of the total surface area of the second face **164** is covered by the electrically conductive cathode paths **178-1** to **178-3**.

In certain embodiments, a plurality of LED chips of an LED array may be mounted on a submount. Each LED chip of the plurality of LED chips is laterally separated from at least one other LED chip of the plurality of LED chips by a first distance, and at least one LED chip of the plurality of LED chips is laterally separated from a first lateral edge of the submount by a second distance that is in a range of about 40% to about 60%, or about 45% to 55%, or about 50% of the first distance. In this regard, multiple submounts may be positioned adjacent to each other, and LED chips on the multiple submounts form an LED array where the first distance is maintained across the multiple submounts within the LED array. In certain embodiments, the second distance is in a range of about 20 μm to about 120 μm. In further embodiments, the second distance is in a range of about 40 μm to about 100 μm. In still further embodiments, the second distance is in a range 50 μm to about 90 μm. Other dimensions for the second distance are possible provided the dimensions are close enough that when multiple submounts are positioned adjacent to one another, the lateral separation of LED chips across the multiple submounts appears uniform. Additionally, a plurality of anode bond pads and a plurality of cathode bond pads may be arranged along one or more lateral edges of a submount. When multiple submounts are arranged together, the plurality of anode and cathode bond pads may be arranged on one or more lateral edges of the submounts that are different from lateral edges where the submounts are joined together.

FIG. **12** is top view of an LED device **188** that includes a first submount **190-1** and a second submount **190-2** that are positioned adjacent to one another. The first submount **190-1** and the second submount **190-2** are similar to the submount **160** of FIGS. **11**A and **11**B. The first submount **190-1** includes a plurality of first LED chip mounting areas **192-1** to **192-3** and the second submount **190-2** includes a plurality of second LED chip mounting areas **194-1** to **194-3**. As before, only some of the first LED chip mounting areas **192-1** to **192-3** and only some of the second LED chip mounting areas **194-1** to **194-3** are numbered for simplicity. Each of the first LED chip mounting areas **192-1** to **192-3** are laterally separated from at least one other of the first LED chip mounting areas **192-1** to **192-3** by a first distance, and at least one of the first LED chip mounting areas **192-1** to **192-3** is laterally separated from a first lateral edge **196** of the first submount **190-1** by a second distance that is about half of the first distance. In particular embodiments, the second distance is in a range of about 40% to about 60%, or about 45% to 55%, or about 50% of the first distance. Other dimensions for the second distance are possible provided the dimensions are close enough that when the submounts **190-1**, **190-2** are positioned adjacent to one another, the lateral separation of subsequently-mounted LED chips across the submounts **190-1**, **190-2** appears uniform. In a similar manner, each of the second LED chip mounting areas **194-1** to **194-3** are laterally separated by the same first distance, and at least one of the second LED chip mounting areas **194-1** to **194-3** is separated from the first lateral edge by the same second distance. In this regard, when the first submount **190-1** and the second submount **190-2** are aligned at the lateral edge **196**, the first distance is maintained between the first LED chip mounting areas **192-1** to **192-3** and the second LED chip mounting areas **194-1** to **194-3** that are closest to the lateral edge **196**. In certain embodiments, the first distance may include a range of about 0.04 mm to about 1 mm. In further embodiments, the first distance may include a range of about 0.04 mm to about 0.5 mm, or a range of about 0.04 mm to about 0.2 mm, or a range of about 0.04 to about 0.12 mm. In certain embodiments, LED chips to be mounted on the submounts **190-1**, **190-2** comprise a longest dimension of about 0.7 mm and the first distance is in a range of about 0.05 mm to about 0.1 mm.

FIG. **13**A is a top view of a submount **198** configured for an individually controllable LED array according to embodiments disclosed herein. FIG. **13**B is a bottom view of the submount **198** of FIG. **13**A. The submount **198** comprises a first face **200** and a second face **202** that opposes the first face **200**. A plurality of LED chip mounting regions **204-1** to **204-3** are on the first face **200** as indicated by the dashed lines in FIG. **13**A. As illustrated, the submount **198** is configured with nine LED chip mounting regions, however only the LED chip mounting regions **204-1** to **204-3** are labeled. A first LED chip mounting region **204-1** includes a first anode **206-1** and a first cathode **208-1**; a second LED chip mounting region **204-3** includes a second anode **206-2** and a second cathode **208-2**; a third LED chip mounting region **204-3** includes a third anode **206-3** and a third cathode **208-3**; and so on. By way of an example, the first anode **206-1** and the first cathode **208-1** are configured to electrically contact a corresponding anode and cathode of an LED chip (not shown) that may be mounted in the first mounting region **204-1**. In certain embodiments, the LED chip mounting regions **204-1** to **204-3** are aligned along a first lateral edge **210** of the submount **198** with a spacing as previously described. The submount **198** additionally includes a second lateral edge **212** and a third lateral edge **214** that are both adjacent the first lateral edge **210**. In certain embodiments, the second lateral edge **212** and the third lateral edge **214** each are substantially perpendicular with the first lateral edge **210** on opposing sides of the submount **198**.

A first anode bond pad **216** and a first cathode bond pad **218** are both arranged on the first face **200** along the second lateral edge **212**, and a second anode bond pad **220** and a second cathode bond pad **222** are both arranged on the first face **200** along the third lateral edge **214**. For simplicity in FIG. **13**A, additional anode bond pads and cathode bond pads are not labeled, however, a plurality of first anode and cathode bond pads may be arranged along the second lateral edge **212** and a plurality of second anode and cathode bond pads may be arranged along the third lateral edge **214** for additional LED chip mounting regions. In this manner, anode and cathode bond pads may be aligned along opposing lateral edges to provide individual control to LED chips mounted on the submount **198**. In other embodiments, anode and cathode bond pads may be aligned along a single edge of the submount **198**. In order to individually control each of the LED chips that will be mounted in the LED chip mounting regions **204-1** to **204-3**, each LED chip mounting region **204-1** to **204-3** is electrically connected with a unique pair of either the first anode bond pad **216** or the second anode bond pad **220** and either the first cathode bond pad **218** or the second cathode bond pad **222**. A first electrically conductive anode path **224** extends between and is continuous with the first anode **206-1** and the first anode bond pad **216**. A first electrically conductive cathode path **226** extends between and is continuous with the first cathode bond pad **218** and both of the first cathode **208-1** and the second cathode **208-2**. A second electrically conductive anode path **228** extends between and is continuous with the second anode bond pad **220** and both of the second anode **206-2** and the third anode **206-3**. Finally, a second electrically conductive cathode path **230** extends between and is continuous with the second cathode bond pad **222** and the third cathode **208-3**. In this manner, an LED chip mounted to mounting region **204-1** may be electrically activated by electrically addressing the first anode bond pad **216** and the first cathode bond pad **218**. An LED chip mounted to the mounting region **204-2** may be electrically activated by electrically addressing the second anode bond pad **220** and the first cathode bond pad **218**. An LED chip mounted to mounting region **204-3** may be electrically activated by electrically addressing the second anode bond pad **220** and the second cathode bond pad **222**. As with previous embodiments, depending on the configuration, the polarities may be reversed such that elements previously referred to as various types of anode elements may be cathode elements and elements previously referred to as anode elements may be cathode elements. Additionally, the first surface **200** may have space for an area **232** that includes identification or other information, including a quick response (QR) code, a bar code, or alphanumeric information.

In contrast to previous embodiments, the second face **202**, or the backside of the submount **198**, is free of electrically conductive paths. Accordingly, the entire second face **202** may be covered with a thermally conductive material for heat dissipation. In other embodiments, at least a portion of the second face **202** may be covered with a thermally conductive material. In still other embodiments, the second face **202** may not include additional materials, rather the second face **202** may be configured to be directly mounted to another surface.

FIG. **14** is top view of a lighting device **233** that includes a plurality of submounts **234-1** to **234-3** that are positioned adjacent to one another. The first submount **234-1**, the second submount **234-2**, and the third submount **234-3** are similar to the submount **198** of FIGS. **13**A and **13**B. A first plurality of LED chips **236** are mounted on the first submount **234-1**, a second plurality of LED chips **238** are mounted on the second submount **234-2**, and a third plurality of LED chips **240** are mounted on the third submount **234-3**. For simplicity, only some of the LED chips **236**, **238**, **240** are labeled, however there are twenty-seven total LED chips **236**, **238**, **240** in FIG. **14**. In other embodiments, the LED chips **236**, **238**, **240** may include any number of LED chips. The first plurality of LED chips **236**, the second plurality of LED chips **238**, and the third plurality of LED chips **240** collectively form an LED array that extends across the plurality of submounts **234-1** to **234-3**. As with previous embodiments, each LED chip **236**, **238**, **240** of the LED array is spaced apart from at least one other LED chip **236**, **238**, **240** of the LED array by a first distance that is consistent for the LED array across the plurality of submounts **234-1** to **234-3**.

According to embodiments disclosed herein, an LED device may include a plurality of submounts, each of which include a plurality of LED chips. As previously described, the plurality of LED chips on each of the submounts collectively forms an LED array across the plurality of submounts. In this manner, additional elements for the LED device may also be formed that extend across the plurality of submounts. For example, one or more light-altering materials as previously described may be continuous on and across each of the plurality of submounts. The one or more light-altering materials may be arranged around an entire perimeter of the LED array as well as in between individual LED chips of the LED array.

FIG. **15** is a top view of a lighting device **242** that includes the plurality of submounts **234-1** to **234-3** and the first plurality of LED chips **236**, the second plurality of LED chips **238**, and the third plurality of LED chips **240** of FIG. **14**. The LED chips **236**, **238**, and **240** collectively form an LED array. The lighting device **242** additionally includes a light-altering material **244** as previously described. The light-altering material **244** is continuous on and across the first submount **234-1**, the second submount **234-2**, and the third submount **234-3**. In certain embodiments, the light-altering material **244** is formed after the plurality of submounts **234-1** to **234-3** are mounted or joined together. In other embodiments, each of the submounts **234-1** to **234-3** may include a portion of the light-altering material **244** before they are mounted or joined together. In this manner, the portions of the light-altering material **244** on each of the submounts **234-1** to **234-3** collectively form the light-altering material **244** that is continuous across the plurality of submounts **234-1** to **234-3**. In certain embodiments where the submounts **234-1** to **234-3** include a portion of the light-altering material **244** before they are mounted or joined together, an additional application of light-altering material may be needed to fill in any gaps in the light-altering material **244** after the submounts **234-1** to **234-3** are assembled together. In certain embodiments, the light-altering material **244** is arranged around an entire perimeter of the first plurality of LED chips **236**, the second plurality of LED chips **238**, and the third plurality of LED chips **240**. Additionally, the light-altering material **244** may be arranged between individual LED chips of the first plurality of LED chips **236**, the second plurality of LED chips **238**, and the third plurality of LED chips **240**. Each LED chip of the first, second, and third plurality of LED chips **236**, **238**, **240** includes a face that is distal to the corresponding submount **234-1** to **234-3** on which it is mounted, and in certain embodiments, the light-altering material **244** does not cover the face. In certain embodiments, each LED chip of the first, second, and third plurality of LED chips **236**, **238**, **240** includes at least one of a growth substrate or a carrier substrate. As with previous embodiments, each of the LED chips **236**, **238**, **240** may include a wavelength conversion element as previously described, and the light-altering material **244** further does not cover a face of each wavelength conversion element that is distal to the corresponding submount **234-1** to **234-3** on which it is mounted. Each of the plurality of submounts **234-1** to **234-3** may be in contact with at least one other submount of the plurality of submounts **234-1** to **234-3**. As previously described, each of the LED chips **236**, **238**, **240** may be arranged on the plurality of submounts **234-1** to **234-3** such that each LED chip **236**, **238**, **240** is laterally separated from at least one other LED chip **236**, **238**, **240** of the LED array by a first distance that is consistent through the LED array. In this manner, the lighting device **242** includes an LED array of individually addressable LED chips **236**, **238**, **240** with improved contrast as different ones of the LED chips **236**, **238**, **240** are electrically activated and electrically de-activated.

While the preceding figures illustrate anode and cathode bond pads aligned along opposing edges of a submount, the anode and cathode bond pads may be aligned along a single edge of the submount in certain embodiments. Additionally, multiple submounts with anode and cathode bond pads aligned along a single edge may be mounted or joined together to form a larger array as previously described. In certain embodiments, a lighting device includes at least a first submount with anode and cathode bond pads aligned along a single edge that is joined or mounted adjacent to at least a second submount with anode and cathode bond pads aligned along opposing edges.

According to embodiments disclosed herein, a lighting device may include a plurality of LED chips arranged on a submount. A light-altering material may be arranged around an entire perimeter of the plurality of LED chips as well as in between individual LED chips on the submount. In certain embodiments, the light-altering material may partially cover the submount, thereby leaving one or more bond pads uncovered in order to facilitate external electrical connections. The arrangement of the submount, the light-altering material, the plurality of LED chips, and one or more bond pads may provide a modular lighting device that can be operated by itself or placed together with other modular LED devices to form a larger lighting device with a larger combined LED array.

FIG. **16** is a top view of a lighting device **246**, or an LED device, that includes the submount **198** of FIG. **13**A, with the plurality of LED chips **236** and the light-altering material **244** of FIG. **15**. As previously described, the submount **198** includes the first anode bond pad **216**, the first cathode bond pad **218**, the second anode bond pad **220**, and the second cathode bond pad **222**. For simplicity in FIG. **16**, additional anode bond pads and cathode bond pads are not labeled. The submount **198** may also include the area **232** that includes identification or other information, including a quick response (QR) code, a bar code, or alphanumeric information. As illustrated, the light-altering material **244** is arranged around an entire perimeter of the plurality of LED chips **236** as well as in between individual LED chips **236** on the submount **198**. Additionally, the first anode bond pad **216**, the first cathode bond pad **218**, the second anode bond pad **220**, and the second cathode bond pad **222** are uncovered by the light-altering material **244** to provide bond pads for external electrical connections. In certain embodiments, the lighting device **246** may be operated on its own. In other embodiments, multiple lighting devices **246** may be placed together in a modular fashion to form a larger array similar to the lighting device **242** of FIG. **15**. In this manner, each individual lighting device **246** includes a light-altering material **244** that is arranged in close proximity to or in contact with a light-altering material **244** from an adjacent lighting device **246**.

As previously described, one or more light-altering materials may be provided between adjacent LED chips to improve contrast. The light-altering material may include light-reflective materials or particles that reflect, refract, or otherwise redirect light, light-absorbing materials that absorb light, and materials that act as a thixotropic agent. In certain embodiments, the light-altering material includes a material or particle that is light reflective or light refractive and light absorbing. For example, the light-altering material may include one or more nanoparticles, mesoparticles, nanowires, and/or mesowires that are configured to refract a portion of light from the LED chips while absorbing another portion of light from the LED chips. As used herein, the term "nanoparticle" generally refers to a particle with a particle size in a range of about 1 nm to about 100 nm, and the term "mesoparticle" generally refers to a particle with a particle size in a range of about 100 nm to about 1000 nm. In a similar manner, the terms "nanopowder" and "mesopowder" generally refer to powdered materials respectively having individual nanoparticles or mesoparticles. As used herein, the term "nanowire" generally refers to a wire structure having a diameter or width in a range of about 1 nm to about 100 nm and an elongated length. In certain embodiments, a nanowire may have a length to width ratio of at least 1000. As used herein, the term "mesowire" generally refers to a wire structure having a diameter or width in a range of about 100 nm to about 1000 nm and an elongated length. In certain embodiments, a mesowire may have a length to width ratio of at least 1000. Nanoparticles and mesoparticles may comprise particles of many different shapes including one or more combinations of wires, spheres, ovals, cubes, pyramids, as well as various asymmetric shapes.

FIG. **17**A is top view of an LED device **248** with one or more LED chips **250-1** to **250-9** arranged on a surface of a submount **252** as previously described. A light-altering material **254** is arranged around a perimeter of the one or more LED chips **250-1** to **250-9** as well as between individual LED chips of the one or more LED chips **250-1** to **250-9**. For example, the light-altering material **254** is arranged around a perimeter or an entire perimeter of the LED chip **250-5**. Additionally, the light-altering material **254** is arranged between the LED chip **250-5** and the other laterally separated LED chips **250-1** to **250-4** and **250-6** to **250-9**. In certain embodiments, the light-altering material **254** is arranged around an entire perimeter of the group of LED chips **250-1** to **250-9**. In certain embodiments, the light-altering material **254** may comprise at least one of a plurality of nanoparticles, a plurality of nanowires, or a plurality of mesowires suspended in a binder such as silicone or epoxy. The plurality of nanoparticles, nanowires, or mesowires may include many different materials including: metallic materials such as nickel (Ni), platinum (Pt), and gold (Au); semiconducting materials such as Si, indium phosphide (InP), and GaN; and insulating materials such as silicon dioxide (SiO_2) and TiO_2. The nanoparticles, nanowires, or mesowires may comprise light-refracting and light-absorbing properties when interacting with light from the one or more LED chips **250-1** to **250-9**. In particular, an individual nanoparticle, nanowire, or mesowire may be configured to refract a portion of light and absorb another portion of light. In certain embodiments, the nanoparticles, nanowires, or mesowires comprise an index of refraction in a range of about 3 to about 5 for a wavelength of about 480 nm. In further embodiments, the nanoparticles, nanowires, or mesowires comprise an index of refraction of about 4 to about 5 for a wavelength of about 480 nm. In certain embodiments, the nanoparticles, nanowires, or mesowires comprise a material such as Si that has a color (e.g. brown, or other non-white and non-black colors) that is partially light absorbing. Accordingly, the nanoparticles, nanowires, or mesowires comprise a high index of refraction for light refraction and a color such as brown that is light-absorbing. A brown color or other non-black or non-white colors provides a narrower absorption spectrum than particles that are black. In this regard, the nanoparticles, nanowires, or mesowires may provide some light-absorbing properties to increase contrast between the LED chips **250-1** to **250-9** while also providing improved brightness when compared to light-absorbing particles that are black. Nanopowders and mesopowders with similar properties to the nanowires and the mesowires may also be present in the light-altering material **254**. Nanopowders and mesopowders may comprise particles of many different shapes including one or more combinations of wires, spheres, ovals, cubes, pyramids, as well as various asymmetric shapes. The light-altering material **254** may additionally comprise a light-reflective and/or light-refractive material that includes at least one of fused silica, fumed silica, TiO_2, or metal particles suspended in the binder. In certain embodiments, the light-altering material **254** includes the following: a binder that comprises silicone with an index of refraction in a range of about 1.3 to about 1.6, or in a range of about 1.4 to about 1.55; a plurality of TiO_2 particles with an index of refraction in a range of about 2.4 to about 3.6; and a silicon nanowire/nanopowder or silicon mesowire/mesopowder mixture having an index of refraction of about 3 to about 5, or in a range of about 4 to about 5, where all of the index or refraction values are for a wavelength of about 480 nm. Accordingly, the light-altering material **254** may include a binder comprising a first index of refraction, one or more light-refracting particles comprising a second index of refraction, and one or more light-refracting and light-absorbing particles having a third index of refraction. In certain embodiments, the second index of refraction is at least two times greater, or in a range of at least two times greater to about three times greater than the first index of refraction. In certain embodiments, the third index of refraction is at least two and a half times greater, or in a range of at least two and a half times greater to about four times greater than the first index of refraction. In certain embodiments, the light-altering material **254** may further comprise metal particles. As previously described, some metal particles are generally more light-reflecting than light-refracting and accordingly have a lower index of refraction. In this regard, the metal particles may have a lower index of refraction than the binder. For example, the light-altering material **254** may further comprise at least one of Al particles that have an index of refraction of about 0.7 or Ag particles that have an index of refraction of about 0.05.

In certain embodiments, the one or more LED chips **250-1** to **250-9** further comprise one or more wavelength conversion elements as previously described. In particular, a first wavelength conversion element may be registered with the LED chip **250-1**, a second wavelength conversion element may be registered with the LED chip **250-2**, and so on. Each of the wavelength conversion elements may comprise a superstrate and a wavelength conversion element as previously described. In this manner, the light-altering material **254** may be arranged around an entire perimeter of each wavelength conversion element, around an entire perimeter of all wavelength conversion elements, as well as between individual wavelength conversion elements. In certain embodiments, the binder (e.g. silicone in certain embodiments) may comprise a weight percent that is in a range of about 10% to about 90% of the total weight of the light-altering material; the light-reflective and/or light-refractive material (e.g. TiO_2 in certain embodiments) may comprise a weight percent that is in a range of about 10% to about 90% of the total weight of the light-altering material; and the nanowires, mesowires, nanopowder, and/or mesopowder (e.g. Si in certain embodiments) may comprise a total weight percent that is in a range of about 0% to about 15% of the total weight of the light-altering material. In further embodiments, the binder may comprise a weight percent that is in a range of about 25% to about 70% of the total weight of the light-altering material; the light-reflective and/or light-refractive material may comprise a weight percent that is in a range of about 25% to about 70% of the total weight of the light-altering material; and the nanowires, mesowires, nanopowder, and/or mesopowder may comprise a weight percent that is in a range of about 0% to about 5% of the total weight of the light-altering material. In further embodiments, the nanowires, mesowires, nanopowder, and/or mesopowder may comprise a weight percent that is in a range of about greater than 0% to about 1% of the total weight of the light-altering material. A weight ratio of the light-reflective or light-refractive material to the binder may comprise a range of about 1:1 to about 2:1. A weight ratio of the nanowires, mesowires, nanoparticles, nanopowder, and/or mesopowder to the binder may comprise a range of about 1:400 to about 1:10. In certain embodiments, the light-altering material may comprise a generally white color with regions of non-white and non-black color (e.g. brown) due to the distribution of nanowires, mesowires, nanopowder, and/or mesopowder.

FIG. **17**B is a line plot of an illumination profile when the LED chip **250-5** is electrically activated, and the LED chips **250-1** to **250-4** and **250-6** to **250-9** are electrically deactivated for two samples with different light-altering materials (**254** of FIG. **17**A). The y-axis of the plot is luminance in candela per square centimeter (cd/cm^2) and the x-axis is the relative distance in millimeters (mm) a sensor moves across the plurality of LED chips **250-1** to **250-9** in a direction as indicated by a dashed line **256** of FIG. **17**A. In FIG. **17**B, Sample 1 represents the LED device **248** of FIG. **17**A where the light-altering material **254** comprises black particles of carbon (also referred to as carbon black), and TiO_2 particles in a binder of silicone. The black particles of carbon have a weight percent of about 0.7% of the total weight of the light-altering material **254**. The TiO_2 and silicone of the remainder of the light-altering material **254** are configured in roughly equal amounts. For Sample 1, the LED chips **250-1** to **250-9** are laterally separated from each other by about 0.1

mm. For Sample 2, the black particles of carbon are replaced with a mixture of silicon nanowires and silicon nanopowder that has a combined weight percent of about 0.7% and the TiO_2 and the silicone amounts are unchanged. In Sample 2, the LED chips **250-1** to **250-9** are laterally separated from each other by about 0.7 mm. In the plot of FIG. **17**B, a first high luminance area **258** indicates the relative position of the LED chip **250-5** that is electrically activated in Sample 1, and a second high luminance area **260** indicates the relative position of the LED chip **250-5** that is electrically activated in Sample 2. At x-axis values of about −0.5 mm and about 0.5 mm, the luminance values sharply decrease, indicating good contrast for both Sample 1 and Sample **2** between the electrically activated LED chip **250-5** and the electrically deactivated LED chips **250-4**, **250-6**. Notably, Sample 2 has a much higher luminance value than Sample 1, indicating that more light is detected from the LED chip **250-5** while still maintaining good contrast with the adjacent LED chips **250-4**, **250-6**. Additionally, Sample 2 is able to achieve this performance with a closer LED chip spacing.

In order to evaluate how the weight percent of a mixture of silicon nanowires and silicon nanopowder in a light-altering material impacts device performance, samples with various weight percents were created and tested. The samples were configured in a similar manner to the lighting device **246** of FIG. **16**. FIG. **18** is a comparison plot showing the relationship of varying weight percents of a silicon nanowire/nanopowder mixture on luminance and contrast ratio in a lighting device. The x-axis of the plot represents the drive current for the lighting device in milliamps (mA). The primary y-axis of the plot is luminance in candela per square millimeters (cd/mm^2). The secondary y-axis represents arbitrary units of a contrast ratio as defined by a ratio of luminance between an electrically activated LED chip (on) and an adjacent LED chip that is electrically deactivated (off). A higher contrast ratio indicates a higher delta between the measured luminance of the electrically activated LED chip compared to the electrically deactivated LED chip. As previously described, the silicon nanowires/nanopowder mixture may have a variety of weight percents of the total light-altering material depending on the desired application. For the purposes of FIG. **18**, silicon nanowires/nanopowder weight percents in a range from greater than 0% to about 1% were measured. In the comparison plot, an arrow **262** indicates the direction of increasing weight percent for the silicon nanowires/nanopowder mixture from greater than 0% to about 1% and the corresponding relationship with contrast ratio. As illustrated, for a fixed drive current, the contrast ratio increases as the weight percent of the silicon nanowires/nanopowder mixture increases. Additionally, for a fixed silicon nanowires/nanopowder mixture weight percent, the contrast ratio remains relatively the same as the drive current increases. An arrow **264** indicates the direction of increasing weight percent for the silicon nanowires/nanopowder mixture from greater than 0% to about 1% and the corresponding relationship with luminance. For a fixed drive current, the luminance decreases as the weight percent of the silicon nanowires/nanopowder mixture increases and for a fixed weight percent of the silicon nanowires/nanopowder mixture, the luminance increases with increased drive current. As shown, there is a trade-off between contrast ratio and luminance as the weight percent of the silicon nanowires/nanopowder mixture is increased. In this manner, the amount of a silicon nanowires/nanopowder mixture in a light-altering material may be tailored based on a desired application.

According to embodiments disclosed herein, a lighting device may include a light-altering material that is arranged between LED chips to provide improved contrast. The light-altering material may include a binder with one or more types of particles that are configured to alter light emitted from the LED chips. When light from the LED chips interacts with the particles, the light may be altered in a variety of manners depending on various configurations of the particles. In certain embodiments, some particles may be configured to substantially refract light from the LED chips, while other particles may be configured to refract light and absorb light from the LED chips, and yet other particles may be configured to substantially reflect light from the LED chips. As previously described, fused silica, fumed silica, and TiO_2 are examples of particles that may be configured to substantially refract light. Nanowires, mesowires, nanoparticles, mesoparticles, nanopowder and mesopowder of silicon or other materials are examples of particles that may be configured to partially refract and partially absorb light, and Al or Ag particles are examples of particles that may be configured to substantially reflect light. In certain embodiments, one or more combinations of different particle types may be combined within the light-altering material such that light from the LED chips that enters the light-altering material may interact with one or more of the different particle types. In this manner, in certain embodiments, an LED device comprises a submount; a first LED chip and a second LED chip on a surface of the submount; wherein the first LED chip is laterally separated from the second LED chip on the surface; and a light-altering material arranged between the first LED chip and the second LED chip on the submount. In certain embodiments, the light-altering material comprises: a binder; one or more first particles configured to substantially refract light emitted from the first LED chip and the second LED chip; and one or more second particles configured to refract light and absorb light emitted from the first LED chip and the second LED chip. In certain embodiments, the light-altering material further comprises one or more third particles configured to substantially reflect light emitted from the first LED chip and the second LED chip.

FIGS. **19**A and **19**B illustrate possible interactions of light within an LED device **266** as disclosed herein. The LED device **266** includes first and second LED chips **268-1**, **286-2** and a light-altering material **270** that is arranged between the LED chips **268-1**, **268-2**. In FIG. **19**A, the light-altering material **270** is illustrated without particles to illustrate light interactions that may occur between the LED chips **268-1**, **268-2** and a binder material of the light-altering material **270**. As previously described, the binder material may include silicone with an index of refraction in a range of about 1.3 to about 1.6, and the LED chips **268-1**, **286-2** may include sapphire material with an index of refraction of about 1.8 or silicon carbide with an index of refraction of about 2.6. The LED chips **268-1**, **286-2** may also include other materials and layers of materials such as wavelength conversion elements or other lumiphoric materials. Light emitting from the LED chips **268-1**, **268-2** may emit or be redirected in all directions before exiting the LED chips **268-1**, **268-2**. Some of the light may exit in a desirable primary emission direction **272**, while other portions of light may attempt to travel laterally from one LED chip **268-1** to another LED chip **268-2** where it may have various interactions with the light-altering material **270**. One or more first light paths **274** may reach an interface **276** between the LED chips **268-1**, **268-2** and the light-altering material **270** with a low angle of incidence and refract back within the LED chips **268-1**, **268-2** and possibly toward the primary emission direction **272**. One or more second light paths **278** may reach the interface **276** with a higher angle of incidence and continue traveling through the light-altering material **270**. If the one or more second light paths **278** ultimately exit between the LED chips **268-1**, **268-2** or into the other of the LED chips **268-1**, **268-2**, then corresponding photons may contribute to parasitic contrast loss. In FIG. **19**B, one or more first particles **280**, one or more second particles **282**, and one or more third particles **284** are illustrated in the light-altering material **270** and between the LED chips **268-1**, **268-2**. In certain embodiments, the one or more first particles **280** are configured to substantially reflect or refract light from the LED chips **268-1**, **268-2**, the one or more second particles **282** are configured to reflect or refract light and absorb light from the LED chips **268-1**, **268-2**, and the one or more third particles **284** are configured to substantially reflect light from the LED chips **268-1**, **268-2**. In this regard, the one or more first particles **280** may comprise a reflectance percentage in a range from about 80% to about 100% for light emitted from the LED chips **268-1**, **268-2**. In further embodiments, the one or more first particles **280** may comprise a reflectance percentage in a range from about 90% to about 100% for light emitted from the LED chips **268-1**, **268-2**. The one or more second particles **282** may comprise a reflectance percentage in a range from about 20% to about 70%, or a range from about 30% to about 60%, or a range from about 35% to about 50% for light emitted from the first LED chip and the second LED chip. As with previous embodiments, the one or more first particles **280** may comprise a weight percent that is in a range of about 10% to about 90%, or in a range of about 25% to about 70% of a total weight of the light-altering material. The one or more second particles **282** may comprise a weight percent that is in a range of about greater than 0% to about 15%, or greater than 0% to about 10%, or greater than 0% to about 5%, or greater than 0% to about 1% of a total weight of the light-altering material. In certain embodiments, a weight ratio of the one or more first particles **280** to the binder may comprise a range of about 1:1 to about 2:1. A weight ratio of the one or more second particles **282** to the binder may comprise a range of about 1:400 to about 1:10. One or more third light paths **286** may enter the light-altering material **270** from the first LED chip **268-1** and interact with the one or more first particles **280** and refract away from the second LED chip **268-2**. One or more fourth light paths **288** may enter the light-altering material **270** and interact with the one or more second particles **282** at an angle of incidence such that photons in the one or more fourth light paths **288** may be absorbed. The one or more second particles **282** may additionally receive photons at one or more fifth light paths **289** that have an angle of incidence where photons may be refracted. One or more sixth light paths **290-1**, **290-2** may interact with the one or more third particles **284** in a manner that photons will reflect. As illustrated by the light paths **289** and **290-2**, photons may be redirected multiple times by one or more of the different particle types **280**, **282**, **284** before exiting in the primary emission direction **272** or being lost to absorption. In some examples, photons may be redirected back into the respective LED chip **268-1**, **268-2** before exiting in the primary emission direction **272**, thereby improving luminance in the primary emission direction **272**. In addition to configurations where the light-altering material **270** includes the one or more first particles **280**, the one or more second particles **282**, and the one or more third particles **284**, the light-altering material **270** may comprise different combinations of particles. For example, the light-altering material **270** may comprise one or more first particles **280** and one or more second particles **282** without the one or more third particles **284** in some embodiments. In other embodiments, the light-altering material **270** may comprise one or more first particles **280** and one or more third particles **284** without the one or more second particles **282**. Additionally, the light-altering material **270** may comprise one or more second particles **282** and one or more third particles **284** in other embodiments without the one or more first particles **280**.

Those skilled in the art will recognize improvements and modifications to the preferred embodiments of the present disclosure. All such improvements and modifications are considered within the scope of the concepts disclosed herein and the claims that follow.

What is claimed is:

1. A light emitting diode (LED) device comprising:

a submount;

a first LED chip on a surface of the submount; and

a first light-altering material arranged around a perimeter of the first LED chip, wherein the first light-altering material comprises a plurality of nanowires and a plurality of mesowires in a binder, wherein the plurality of nanowires and the plurality of mesowires are configured to primarily absorb visible light in a first wavelength range and primarily refract visible light in a second wavelength range that is different than the first wavelength range, wherein the plurality of nanowires and the plurality of mesowires comprise a mixture that is configured with an index of refraction in a range from 3 to 5 for a wavelength of 480 nanometers (nm).

2. The LED device of claim **1**, wherein the plurality of nanowires comprises silicon nanowires.

3. The LED device of claim **1**, wherein the plurality of mesowires comprises silicon mesowires.

4. The LED device of claim **1**, wherein the first light-altering material further comprises at least one of a nanopowder or a mesopowder.

5. The LED device of claim **4**, wherein a total weight percent of the plurality of nanowires, the plurality of mesowires, the nanopowder, or the mesopowder is in a range of greater than 0% to 15% of a total weight of the first light-altering material.

6. The LED device of claim **1**, wherein the first light-altering material further comprises at least one of fused silica, fumed silica, titanium dioxide (TiO_2), or metal particles in the binder.

7. The LED device of claim **1**, further comprising a first wavelength conversion element registered with the first LED chip, wherein the first wavelength conversion element comprises a first superstrate and a first lumiphoric material that is arranged between the first superstrate and the first LED chip.

8. The LED device of claim **7**, wherein the first light-altering material is further arranged around a perimeter of the first wavelength conversion element.

9. The LED device of claim **1**, further comprising a second LED chip on the surface of the submount and wherein the first light-altering material is arranged between the first LED chip and the second LED chip.

10. The LED device of claim **1**, wherein the first light-altering material comprises the plurality of nanowires and a plurality of particles that are configured to primarily refract visible light.

11. The LED device of claim **10**, wherein the plurality of nanowires comprises nanowires that are non-white and non-black in color and the plurality of particles comprises white particles.

12. A light emitting diode (LED) device comprising:

a submount;

a first LED chip and a second LED chip on a surface of the submount, wherein the first LED chip is laterally separated from the second LED chip on the surface; and

a first light-altering material arranged between the first LED chip and the second LED chip on the submount, wherein the first light-altering material comprises a plurality of nanoparticles in a binder, and the plurality of nanoparticles is configured to primarily absorb visible light in a first wavelength range and primarily refract visible light in a second wavelength range that is different than the first wavelength range, wherein the plurality of nanoparticles comprises a reflectance percentage in a range from 35% to 50% for light emitted from the first LED chip and the second LED chip.

13. The LED device of claim **12**, wherein the plurality of nanoparticles comprises silicon nanoparticles.

14. The LED device of claim **13**, wherein a total weight percent of the plurality of nanoparticles is in a range of greater than 0% to 15% of a total weight of the first light-altering material.

15. The LED device of claim **12**, wherein the plurality of nanoparticles comprise shapes including one or more combinations of wires, spheres, ovals, cubes, pyramids, and asymmetric shapes.

16. The LED device of claim **12**, wherein the first light-altering material further comprises at least one of fused silica, fumed silica, titanium dioxide (TiO_2), or metal particles in the binder.

17. The LED device of claim **12**, wherein the first light-altering material is arranged around an entire perimeter of the first LED chip and around an entire perimeter of the second LED chip.

18. The LED device of claim **12**, further comprising:

a first wavelength conversion element registered with the first LED chip, wherein the first wavelength conversion element comprises a first superstrate and a first lumiphoric material that is arranged between the first superstrate and the first LED chip; and

a second wavelength conversion element registered with the second LED chip, wherein the second wavelength conversion element comprises a second superstrate and a second lumiphoric material that is arranged between the second superstrate and the second LED chip.

19. The LED device of claim **18**, wherein the first light-altering material is further arranged between the first wavelength conversion element and the second wavelength conversion element.

20. The LED device of claim **12**, wherein the first light-altering material further comprises a plurality of particles that are configured to primarily refract visible light.

21. The LED device of claim **20**, wherein the plurality of nanoparticles comprises nanoparticles that are non-white and non-black in color and the plurality of particles comprises white particles.

22. A light emitting diode (LED) device comprising:

a submount;

a first LED chip and a second LED chip on a surface of the submount, wherein the first LED chip is laterally separated from the second LED chip on the surface; and

a first light-altering material arranged between the first LED chip and the second LED chip on the submount, wherein the first light-altering material comprises:

a binder comprising a first index of refraction;

one or more first particles comprising a second index of refraction; and

a plurality of second particles comprising a mixture of nanoparticles and mesoparticles with a third index of refraction, wherein the plurality of second particles are configured to primarily absorb visible light in a first wavelength range and primarily refract visible light in a second wavelength range that is different than the first wavelength range;

wherein the second index of refraction is at least two times greater than the first index of refraction, and the third index of refraction is at least two and a half times greater than the first index of refraction, wherein the third index of refraction is in a range from 3 to 5 for a wavelength of 480 nanometers (nm).

23. The LED device of claim **22**, wherein the second index of refraction is in a range of at least two times greater to three times greater than the first index of refraction, and the third index of refraction is in a range of at least two and a half times greater to four times greater than the first index of refraction.

24. The LED device of claim **22**, wherein the one or more first particles comprise at least one of fused silica, fumed silica, and titanium dioxide (TiO_2).

25. The LED device of claim **22**, wherein the plurality of second particles comprise at least one of nanowires and mesowires.

26. The LED device of claim **22**, wherein the first light-altering material is arranged around an entire perimeter of the first LED chip and around an entire perimeter of the second LED chip.

27. The LED device of claim **22**, wherein the first light-altering material further comprises metal particles.

28. A light emitting diode (LED) device comprising:

a submount;

a first LED chip and a second LED chip on a surface of the submount, wherein the first LED chip is laterally separated from the second LED chip on the surface; and

a light-altering material arranged between the first LED chip and the second LED chip on the submount, wherein the light-altering material comprises:

a binder;

one or more first particles configured to primarily reflect or refract light emitted from the first LED chip and the second LED chip; and

one or more second particles configured to primarily reflect or refract a first portion of light emitted from the first LED chip and the second LED chip and primarily absorb a second portion of light emitted from the first LED chip and the second LED chip, wherein the one or more second particles comprise a reflectance percentage in a range from 35% to 50% for light emitted from the first LED chip and the second LED chip.

29. The LED device of claim **28**, wherein the one or more first particles comprise at least one of fused silica, fumed silica, or titanium dioxide (TiO_2).

30. The LED device of claim **28**, wherein the one or more second particles comprise at least one of nanowires, mesowires, nanoparticles, mesoparticles, nanopowder, or mesopowder.

31. The LED device of claim **28**, wherein the light-altering material further comprises one or more third particles configured to primarily reflect light emitted from the first LED chip and the second LED chip.

32. The LED device of claim **31**, wherein the one or more third particles comprise metal particles.

33. The LED device of claim **28**, wherein the one or more first particles comprise a reflectance percentage in a range from 80% to 100% for light emitted from the first LED chip and the second LED chip.

34. The LED device of claim **28**, wherein the one or more first particles comprise a weight percent that is in a range of 10% to 90% of a total weight of the light-altering material.

35. The LED device of claim **28**, wherein the one or more first particles comprise a weight percent that is in a range of 25% to 70% of a total weight of the light-altering material.

36. The LED device of claim **28**, wherein the one or more second particles comprise a weight percent that is in a range of greater than 0% to 15% of a total weight of the light-altering material.

37. The LED device of claim **28**, wherein the one or more second particles comprise a weight percent that is in a range of greater than 0% to 10% of a total weight of the light-altering material.

38. The LED device of claim **28**, wherein the one or more second particles comprise a weight percent that is in a range of greater than 0% to 5% of a total weight of the light-altering material.

39. The LED device of claim **28**, wherein the one or more second particles comprise a weight percent that is in a range of greater than 0% to 1% of a total weight of the light-altering material.

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